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a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 301-405-1610

RPPR Final Report
as of 09-May-2018

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Final Report for Period Beginning 18-Nov-2016 and Ending 17-Nov-2017

Title: Conference: Dynamics Days 2017

Begin Performance Period: 18-Nov-2016

End Performance Period: 17-Nov-2017

Report Term: 0-Other

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STEM Degrees: 0

STEM Participants: 30

Major Goals: Dynamics Days is an annual conference whose purpose is to gather a variety of researchers with overlapping interests in topics in nonlinear dynamics. It has become well known in the field as a highly productive way for researchers with common interests but varied background to disseminate their own results and learn about recent developments in related areas. Though the regular attendees are primarily in the fields of mathematics and physics, the interdisciplinary field of nonlinear dynamics has continued to grow rapidly in recent years, expanding to other disciplines. This is in part due to the development of more sophisticated analytical and numerical techniques and more refined experimental procedures that permit the study of systems with greater complexity. Invited speakers in the Dynamics Days Conference series include researchers in physics, mathematics, chemistry, engineering, fluid mechanics, biology, physiology and economics.

Accomplishments: The ARO-funded International Conference on Chaos and Nonlinear Dynamics: Dynamics Days 2017, which was held at the Sheraton Silver Spring Hotel, January 4 – 6, 2017, and hosted by the University of Maryland (UMD) was a tremendous success with over 140 registered participants from across the country and across the world.

Organization: Dynamics Days 2017 was co-organized by UMD professors Michelle Girvan (PI) and Dan Lathrop (Co-PI). In addition to Girvan and Lathrop the organizing committee included Ed Ott (UMD), Raj Roy (UMD), Wolfgang Losert (UMD), Brian Hunt (UMD), Lou Pecora (Naval Research Lab) and Ernier Barreto (George Mason University). The organizing committee was responsible for selecting speakers (invited, contributed, and ignite) and posters. The meeting was announced using the conference webpage (<https://ireap.umd.edu/DDays2017>), email announcements to past attendees, a mailing of a poster advertising the meeting to key graduate departments in physics and math in the US, and through appropriate professional societies announcements.

Structure and Focus of Dynamics Days 2017: For Dynamics Days 2017, we had 14 invited speakers who each gave talks of 35 minutes each, an additional 15 contributed oral presentations of 15 minutes each, and over 100 posters. In addition to these presentations, which have historically been included in the annual Dynamics Days conference, we also included 20 5-minute Ignite talks to this year's program. These talks, for which researchers submit 20 slides that auto-advance at 15-second intervals, have been demonstrated by other conferences to be a

RPPR Final Report

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successful vehicle for young researchers to present their results in a high-profile setting. This new addition was highly regarded by both attendees and presenters. The full Dynamics Days 2017 schedule covered a broad range of topics, including pattern forming systems, characterization and control of networks, synchronization of nonlinear systems, and the dynamics of living systems.

Training Opportunities: The ARO funding provided travel support for 30 students and postdocs to attend Dynamics Days 2017. This gave young researchers opportunities to develop, practice, and exhibit their science communication skills.

Results Dissemination: Dissemination was achieved through the conference itself. See <https://ireap.umd.edu/DDays2017> for more details

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Michelle Girvan

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Final report for ARO funded conference: Dynamics Days 2017

The ARO-funded International Conference on Chaos and Nonlinear Dynamics: ***Dynamics Days 2017***, which was held at the Sheraton Silver Spring Hotel, January 4 – 6, 2017, and hosted by the University of Maryland (UMD) was a tremendous success with over 140 registered participants from across the country and across the world.

Dynamics Days is an annual conference whose purpose is to gather a variety of researchers with overlapping interests in topics in nonlinear dynamics. It has become well known in the field as a highly productive way for researchers with common interests but varied background to disseminate their own results and learn about recent developments in related areas. Though the regular attendees are primarily in the fields of mathematics and physics, the interdisciplinary field of nonlinear dynamics has continued to grow rapidly in recent years, expanding to other disciplines. This is in part due to the development of more sophisticated analytical and numerical techniques and more refined experimental procedures that permit the study of systems with greater complexity. Invited speakers in the Dynamics Days Conference series include researchers in physics, mathematics, chemistry, engineering, fluid mechanics, biology, physiology and economics.

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Invited speakers: As mentioned above, our invited speakers were drawn from experimental, theoretical, and computational domains, and focus on a variety of applications related to nonlinear science. Our invited speakers for Dynamics Days 2017 were: Danielle Bassett (Penn), James Langer (UCSB), Eva-Maria Schoetz Collins (UCSD), Zvonimir Dogic (Brandeis), David Levermore (UMD), Robin Selinger (Kent State), Flavio Fenton (Georgia Tech), Yang-Yu Liu (Harvard), Woodrow Shew (Arkansas), Christopher Jarzynski (UMD), Mason Porter (UCLA), Istvan Szunyogh (Texas A&M), Juergen Kurths (Potsdam), and Derek Richardson (UMD).

Funding: Funding for Dynamics Days 2017 came from the Army Research Office (ARO), the University of Maryland, and Registration fees. Registrations fees were modest in comparison to similar meetings (\$150 per person for students and postdocs and \$250 per person for others for early registration) and were used largely to cover the cost of refreshments between oral presentations and at the poster sessions. The ARO funding helped to cover the travel and local expenses for 10 invited speakers and provided travel support for 30 students and postdocs. A small amount of the ARO funding was also applied to audio-visual expenses, materials (pens, folders, programs, etc.), and conference management software.

Dynamics Days 2017 Schedule

Check-in and registration desk will be open during the following times:

Wednesday: 8:15am – 4:15pm (except noon – 1pm)

Thursday: 8:30am – 11:30am and 1pm – 1:45pm

Friday: 8:30am – 11:30am

Wednesday January 4

8:15	8:45		Check-in + On-site registration <i>coffee and pastries available</i>	
8:45	9:00		Welcome	Michelle Girvan
9:00	9:35	1	Invited: A developmental arc of white matter supporting a growing diversity of brain dynamics	Danielle Basset (Penn)
9:35	9:55	2	Contributed: Persistent structures and piecewise isometries in 3D mixing systems	Paul Umbanhowar
9:55	10:30	3	Invited: Dynamic Instabilities in Dislocation-Enabled Plasticity	James Langer (UCSB)
10:30	11:00		Break	
11:00	12:00	4-13	Ignite Session A	
12:00	1:45		Lunch break	
1:45	2:20	14	Invited: Simulating Granular Dynamics in Very Low Gravity	Derek Richardson (UMD)
2:20	2:40	15	Contributed: Specific Transfer Entropy and Its Estimation from Empirical Data	David Darmon
2:40	3:00	16	Contributed: A network approach to pattern formation in atmospheric cloud fields	Franziska Glassmeier
3:00	4:15	17-61	Poster Session A	
4:15	4:35	62	Contributed: Dynamics in a two-step epidemic model: Universal mechanism for hybrid percolation transitions induced by cascade dynamics	Byungnam Kahng
4:35	5:10	63	Invited: Quantifying the Predictability of Precipitation	Istvan Szunyogh (Texas A&M)
5:10	5:30	64	Contributed: A Geometrical Description of Turbulence Using Exact Coherent Structures	Balachandra Suri

The entire conference will be held on the 4th floor of the Sheraton Silver Spring Hotel

All Invited, Contributed and Ignite will be in Cypress Ballroom

All Posters will be in Magnolia Ballroom

Breaks will include complimentary coffee | Lunch is on your own

Thursday January 5

8:30	9:00		Check-in + On-site registration <i>coffee and pastries available</i>	
9:00	9:35	65	Invited: Period Doubling Bifurcations in Cardiac Tissue; Experiments, Theory and Simulations	Flavio Fenton (Georgia Tech)
9:35	9:55	66	Contributed: Computational Mechanics of Coherent Structures in Spatiotemporal Systems	Adam Rupe
9:55	10:30	67	Invited: Snakes on a plane: modeling flexible active nematics	Robin Selinger (Kent State)
10:30	11:00		Break	
11:00	12:00	68-77	Ignite Session B	
12:00	1:45		Lunch break	
1:45	2:20	78	Invited: An adaptive computational trade-off in turtle visual cortex	Woodrow Shew (Arkansas)
2:20	2:40	79	Contributed: Echo Behavior in Large Populations of Chemical Oscillators	Kenneth Showalter
2:40	3:15	80	Invited: Scattering Theory for the Boltzmann Equation and the Arrow of Time	David Levermore (UMD)
3:15	3:35	81	Contributed: Dimension from Covariance Matrices	Tom Carroll
3:35	4:00		Break	
4:00	4:35	82	Invited: Spontaneous flows in soft active matter	Zvonimir Dogic (Brandeis)
4:35	4:55	83	Contributed: Temporal Diffraction Signatures of <i>C. elegans</i>	Jenny Magnes
4:55	5:30	84	Invited: Ripping yourself a new one: Dynamics of Mouth Opening in Hydra	Eva-Maria Schoetz Collins (UCSD)

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Friday January 6

8:30	9:00		Check-in + On-site registration <i>coffee and pastries available</i>	
9:00	9:35	85	Invited: Predictability of Extreme Rainfall Events via a Complex Network Approach	Juergen Kurths (Potsdam)
9:35	9:55	86	Contributed: Energy Harvesting from Limit Cycle Oscillations of a Flexible Structure in a Fluid Flow	Earl Dowell
9:55	11:10	87-129 + LB	Poster Session B	LB = Late-breaking
11:10	11:45	130	Invited: Controlling Human Microbiota	Yang-Yu Liu (Harvard)
11:45	12:05	131	Contributed: Symmetric States Requiring System Asymmetry	Takashi Nishikawa
12:05	1:50		Lunch break	
1:50	2:25	132	Invited: Fast forward to the classical adiabatic invariant	Christopher Jarzynski (UMD)
2:25	2:45	133	Contributed: Flame surface patterns during thermoacoustic instability	Lipika Kabiraj
2:45	3:05	134	Contributed: Finite-time Thin Film Rupture Driven by Modified Evaporative Loss	Hangije Ji
3:05	3:35		Break	
3:35	3:55	135	Contributed: Multi Chaos: A Low-Dimensional Paradigm for High Dimensional Chaos	James Yorke
3:55	4:15	136	Contributed: Interactions of Solitary Pulses of E. coli in a One-Dimensional Nutrient Gradient	Glenn Young
4:15	4:50	137	Invited: A Simple Generative Model for Collective Online Behavior	Mason Porter (UCLA)

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All Invited, Contributed and Ignite will be in Cypress Ballroom

All Posters will be in Magnolia Ballroom

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Ignite Session A order
(Wednesday January 4, 11am – noon)

4	Direct and Indirect Effects of Topography on the Dynamics of Mesoscale Eddies – Larry Gulliver (Also in Poster Session A)
5	Quantum Chaos in Clifford Circuits – Michael Walter
6	Tangled up in Blue: High Frequency Intermittent FPU Dynamics at Equilibrium – David Campbell
7	Numerical Simulations of Oscillation-Driven Regolith Motion on Asteroids – Ronald Ballouz
8	Connecting Hyperbolic Geometry to Kuramoto Oscillator Systems: New Classes of Gradient Phase Models and Completely Integrable Dynamics – Bolun Chen (Also in Poster Session A)
9	The onset of chaos in orbital pilot-wave dynamics – Anand Oza
10	Observing Chaos When the Dynamics of the System is Unknown: A Reservoir Computing Approach – Jaideep Pathak (Also in Poster Session A)
11	State-dependent intrinsic predictability of cortical network dynamics – Leila Fakhraei (Also in Poster Session A)
12	Using data-driven models of brain function to predict individual differences in cognitive task performance – Kanika Bansal (Also in Poster Session A)
13	Sub-threshold resonance facilitates sequential learning in biophysical neural networks. – James Roach (Also in Poster Session A)

Ignite Session B order
(Thursday January 5, 11am – noon)

68	When Not to Grab the Bull by the Horns: Indirect Targeting in Networks – Sean Cornelius
69	Multivariate Dependence Beyond Shannon Information – Ryan James
70	Large Deviations for Gaussian Diffusions with Delay – Brett Geiger
71	Effects of Signal Inhibition on Collective Cell Migration in the Posterior Lateral Line Primordium of danio rerio – Deborah Hemingway (Also in Poster Session B)
72	Agent-based models of pattern formation on zebrafish – Alexandria Volkening (Also in Poster Session B)
73	Large Fluctuations and Rare-Events in Complex Networks – Jason Hinds (Also in Poster Session B)
74	A network dynamics approach to identifying minimal functional subnetworks – Rasoul Rajaei (Also in Poster Session B)
75	The amplification of intrinsic noise by chaos in an optoelectronic feedback loop – Kevin Fei (Also in Poster Session B)
76	Inhibitory Neurons Promote Robust Critical Firing Dynamics in Networks of Integrate-and-Fire Neurons – Zhixin Lu
77	Leveraging Environmental Correlations: The Thermodynamics of Requisite Variety – Alexander Boyd

Session A Posters (Wednesday January 4, 3pm – 4:15pm)		
17	The Time Delayed Ensemble Kalman filter for nonlinear Estimation	Zhe An and Henry Abarbanel
18	Nonlinear Dynamics of Macroscopic Quantum Superconducting Metamaterials	Steven Anlage, Daimeng Zhang, Melissa Trepanier, Edward Ott and Thomas Antonsen
19	Hidden Structures of Information Transport Underlying Spiral Wave Dynamics	Hiroshi Ashikaga and Ryan James
20	Using data-driven models of brain function to predict individual differences in cognitive task performance	Kanika Bansal, John Medaglia, Danielle Bassett, Jean Vettel and Sarah Muldoon
21	A Simple approach of Destriping Remote Sensing Imagery	Ranil Basnayake, Erik Bollt, Nick Tufillaro and Jie Sun
22	Ensemble Kalman filtering without a model	Franz Hamilton, Tyrus Berry and Timothy Sauer
23	Chaotic Time Series Prediction with FPGA-Based Reservoir Computers	Daniel Canaday, Aaron Griffith and Daniel Gauthier
24	Connecting Hyperbolic Geometry to Kuramoto Oscillator Systems: New Classes of Gradient Phase Models and Completely Integrable Dynamics	Bolun Chen, Jan Engelbrecht and Renato Mirollo
25	Nonlinear Dynamics in Optimal Communication Waveforms	Ned Corron and Jonathan Blakely
26	Lagrangian descriptors of time-dependent transition states	Galen Craven
27	Transport, Diffusion, and Energy in the Arnold-Beltrami-Childress map	Swetamber Das and Neelima Gupte
28	State-dependent intrinsic predictability of cortical network dynamics	Leila Fakhraei, Shree Hari Gautam and Woodrow Shew
29	Experimental Study of Quantum Graphs With and Without Time-Reversal Invariance	Ziyuan Fu, Trystan Koch, Thomas Antonsen, Edward Ott and Steven Anlage
30	Perron-Frobenius meet Monge-Kantorovich: A set-oriented graph-based approach to optimal transport	Piyush Grover and Karthik Elamvazhuthi
31	Direct and Indirect Effects of Topography on the Dynamics of Mesoscale Eddies.	Larry Gulliver, Timour Radko and Justin Brown
32	Implementation of a Chaotic Equation in High Speed Electronics	Chase Harrison, Benjamin Rhea, Frank Werner and Robert Dean
33	Dynamics of small networks of biomimetic artificial neurons	Harold Hastings, Oscar Hernandez, Lucy Jiang and Lindsey Tensen
34	Invasion fronts in the Fisher-KPP equation on homogeneous trees and random graphs	Aaron Hoffman and Matt Holzer
35	Dynamic Diffraction Analysis of <i>C. elegans</i>	Miranda Hulsey-Vincent, Clara Alivisatos, Kathleen Susman and Jenny Magnes
36	Optimal target sets for a random walk on an undirected graph	Fern Hunt
37	Coupled Autocatalytic Reactions: Interconversion and Extinction of Species	Aditi Khot and S Pushpavanam
38	Using the permutation entropy to detect nonlinearity in short and noisy time series data	Luciano Zunino and Christopher Kulp
39	Relativistic quantum kicked rotor	Boon Leong Lan
40	Collective cell migration over long time scales reveals distinct phenotypes	Rachel Lee, Christina Stuelten, Carole Parent and Wolfgang Losert
41	Analytic Solutions Throughout A Period Doubling	Marko Milosavljevic, Jonathan Blakely

	Route to Chaos	and Ned Corron
42	Bayesian approach for information theory to explain temporal dynamic between stimuli in EEG/MEG signals	Carlos Mugruza-Vassallo
43	Size-dependent properties of branching of tadpole-like Physarum plasmodium.	Msahide Okada and Tatsunari Sakurai
44	Observing Chaos When the Dynamics of the System is Unknown: A Reservoir Computing Approach	Jaideep Pathak, Zhixin Lu, Brian Hunt, Michelle Girvan, Roger Brockett and Edward Ott
45	Constructing quantum shortcuts to adiabaticity using classical dynamics	Ayoti Patra and Christopher Jarzynski
46	Finding and Forming Synchronized Clusters in Complex Networks of Oscillators Using Symmetries	Louis Pecora, Francesco Sorrentino, Aaron Hagerstrom, Rajarshi Roy and Thomas Murphy
47	Symbolic template iterations of complex quadratic maps	Anca Radulescu and Ariel Pignatelli
48	Real and complex behavior for networks of coupled logistic maps	Anca Radulescu and Ariel Pignatelli
49	Modelling paradoxical excitation under general anesthesia as an inverse response phenomenon	Aditi Khot, Roshan M. Regy and S Pushpavanam
50	Sub-threshold resonance facilitates sequential learning in biophysical neural networks.	James Roach and Michal Zochowski
51	Noisy dynamics of thermoacoustic systems prior to Hopf bifurcation	Aditya Saurabh and Lipika Kabiraj
52	Construction of Reduced Dynamics Models from High-Dimensional Time Series	Aleksei Seleznev, Dmitry Mukhin, Andrey Gavrilov and Alexander Feigin
53	Examining Human Unipedal Quiet Stance	Matthew Semak, Jeremiah Schwartz, Taylor McMillan and Gary Heise
54	Quantum vortex visualization experiment	Itamar Shani, Peter Megson and Daniel Lathrop
55	Entrainment of Coupled Oscillators	Jordan Snyder
56	A developmental arc of white matter supporting a growing diversity of brain dynamics	Evelyn Tang, Chad Giusti, Graham Baum, Shi Gu, Eli Pollock, Ari Kahn, David Roalf, Tyler Moore, Kosha Ruparel, Ruben Gur, Raquel Gur, Theodore Satterthwaite and Danielle Bassett
57	Resource-transport dynamics induces criticality in networks of excitable nodes	Yogesh Virkar, Woodrow Shew, Juan Restrepo and Edward Ott
58	Wavenumber Selection via Spatial Parameter Step	Jasper Weinrich-Burd and Arnd Scheel
59	Dynamics of a Human Spiral Wave	Andrea Welsh, Edwin Greco and Flavio Fenton
60	Testing Wave Chaos Statistical Predictions in Scaled Electromagnetic Cavities	Bo Xiao, Thomas Antonsen, Edward Ott, Zachary Drikas, Jesus Gil Gil and Steven Anlage
61	Characterization of BZ Reaction Phase Response Curves and Synchronization of Coupled BZ Oscillators	Desmond Yengi, Jirapa Rueangsuwan, Mark Tinsley and Kenneth Showalter

Session B Posters
(Friday January 6, 9:55am – 11:10am)

87	Experiments in Superconducting Microwave Cavities to demonstrate Chaos Regularization of Quantum Tunneling Rates	Bisrat Addissie
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88	Principles governing neural dynamics are scale-invariant at criticality: Renormalization approach.	Vidit Agrawal
89	Complex behavior in networks of nonlinear oscillators	Leandro Alonso
90	Crash Box Response to a Drop Weight Impact Tester	Khaled Asfar, Salman Hailat and Mai Al-Qudah
91	Phases of Space-occupying networks and relation to mammalian brain	Nima Dehmamy, Soodabeh Milanloui and Laszlo Barabasi
92	Spectral Properties of Spiral Waves in the Barkley Model	Stephanie Dodson and Bjorn Sandstede
93	The amplification of intrinsic noise by chaos in an optoelectronic feedback loop	Kevin Fei, Joe Hart, Thomas Murphy and Rajarshi Roy
94	A Novel Model of Pulsing Oscillators	Christopher Fritz
95	Graph clustering of human mobility networks and its applications	Naoya Fujiwara
96	Limit cycles and strange attractors of polynomial dynamical systems	Valery Gaiko
97	Handwritten Digit Recognition with Reservoir Computers in Software and Hardware	Aaron Griffith, Nicholas Haynes, Otti D'Huys, Daniel Canaday and Daniel Gauthier
98	Chaos, noise, and physical random number generation	Joseph Hart, Yuta Terashima, Atsushi Uchida, Thomas Murphy and Rajarshi Roy
99	Modeling the Network Dynamics of Pulse-Coupled Neurons	David Hathcock, Kimberly Crain, Sarthak Chandra, Thomas Antonsen, Edward Ott and Michelle Girvan
100	Effects of Signal Inhibition on Collective Cell Migration in the Posterior Lateral Line Primordium of danio rerio	Deborah Hemingway, Rachel Lee and Wolfgang Losert
101	Large Fluctuations and Rare-Events in Complex Networks	Jason Hindes and Ira Schwartz
102	Effects of traumatic brain injury upon the neural dynamics and nonlinear network properties of the human brain	Andrei Irimia and John Van Horn
103	Control of diffusion in random walkers	Miki Kobayashi and Hiroyasu Ando
104	Tunable Photonic Oscillators	Vassilios Kovanis
105	Turbulent Chimera States in Large Diode Lasers Arrays	Vassilios Kovanis
106	Development of kinks in car-following models	Douglas Kurtze
107	Statistics of chaotic resonances at optical frequencies: theory and experiments	Domenico Lippolis, Li Wang and Yun-Feng Xiao
108	Nonlinear Dynamics of Directed Cell Migration	Wolfgang Losert
109	The Impact of Non-Orthogonal Axes on Mixing with a Bi-axial Hemispherical Piecewise Isometry	Thomas Lynn, Julio Ottino, Paul Umbanhowar and Richard Lueptow
110	Burning up: The effect of slope upon forest fire propagation	Robin M.P. Morillo and Niklas Manz
111	Spontaneous oscillation in coupled heterogeneous excitable phase oscillators	Kai Morino, Gouhei Tanaka and Kazuyuki Aihara
112	Revisiting delay-embedding by using Hilbert-Schmidt integral operator theory for dynamical reconstruction	Naoto Nakano
113	Dynamics of free scroll wave termination by low-energy electric field pulses in three dimensions	Niels Otani, Valentin Krinski, Kayleigh Wheeler and Stefan Luther
114	Phase synchronization in active and quiet sleep in	Nicoló Pini, Maristella Lucchini, Nina

	newborn infants	Burtchen and Maria Gabriella Signorini
115	Boolean Satisfiability as Boolean Networks	Andrew Pomerance
116	Dynamical rhythms of an array of diffusively coupled BZ microoscillators with Global Negative Feedback.	Ivan Proskurkin and Vladimir K. Vanag
117	A network dynamics approach to identifying minimal functional subnetworks	Rasoul Rajaei, Sean Cornelius, Emma Towlson and Albert-László Barabási
118	Optimal dynamical regularization for prediction in nonlinear inverse problems	Paul Rozdeba
119	Propagating ring and deposition pattern of motile cells of Escherichia coli	Tatsunari Sakurai
120	Collective motion patterns and hybrid dynamics of swarms with networked delay coupling	Ira Schwartz, Klementyna Szwaykowska and Jason Hinds
121	Prediction of Indian Summer Monsoon Rainfall by Phase-Space Reconstruction Model	V. Krishnamurthy and A. Surjalal Sharma
122	Study of Phase-flip and oscillation-death in indirectly coupled oscillators	Amit Sharma, Umesh Verma and Manish Shrimali
123	Memory Stabilization Preferentially Occurs Near a Phase-Transition	Quinton Skilling, Nicolette Ognjanovski, Sara Aton and Michal Zochowski
124	Wrinkling of a thin film on a nematic liquid crystal elastomer	Harsh Soni, Robert A Pelcovits and Thomas R. Powers
125	Dynamics of a Two-Layer Tear Film with Evaporation	Michael Stapf
126	Four wave interaction system makes wrong predictions for the water wave problem	Danish Ali Sunny
127	Agent-based models of pattern formation on zebrafish	Alexandria Volkening and Bjorn Sandstede
128	Mathematical Model of Glob-Driven Tear Film Breakup (TBU)	Lan Zhong, Christiaan F. Ketelaar, Richard J. Braun, Carolyn G Begley and P. Ewen King-Smith
129	Nonlinear Wave Chaos and the Random Coupling Model	Min Zhou, Edward Ott, Thomas M. Antonsen and Steven M. Anlage

Late-Breaking Posters
(Friday January 6, 9:55am – 11:10am)

LB1	Coarse Modeling of Circadian Rhythms in Heterogeneous Neural Networks	Tom Bertalan, C. William Gear, Yannis Kevrekidis, Michael Henson, Erik Herzog and Carlo Laing
LB2	Parameter reduction via nonlinear data-mining	Alexander Holiday, Antonios Zagaris, William Leeb, William Gear and Ioannis Kevrekidis
LB3	Bifurcations in a periodically stimulated limit cycle oscillator with finite relaxation times	Peter Langfield, Wilson Facanha, Bart Oldeman and Leon Glass
LB4	Using a Large-Scale Neural Model of Cortical Object Processing to Investigate the Neural Substrate for Holding Multiple Items in Short-Term Memory and for performing a Paired Associate Task	Qin Liu, Antonio Ulloa and Barry Horwitz
LB5	Data-Mining Assisted Coarse-Grained Optimization	Dmitry Pozharskiy, Andrew Duncan, Grigorios A. Pavliotis and Ioannis G. Kevrekidis
LB6	Suppression and revival of oscillation in indirectly coupled limit cycle oscillators	Pooja Rani, Neeraj Kamal and Manish Shrimali
LB7	Ordinal Networks of Time Series	Michael Small, Konstantinos Sakellariou, Michael McCullough and Thomas Stemler

DYNAMICS DAYS 2017

January 4 -6, 2017

Sheraton Silver Spring, MD

ABSTRACTS

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1

Invited Talk (Wednesday)

A developmental arc of white matter supporting a growing diversity of brain dynamics*Danielle Bassett*Presenter: *Danielle Bassett / University of Pennsylvania*

As the human brain develops, it increasingly supports the coordinated synchronization and control of neural activity. The mechanism by which white matter evolves to support this coordination is not well understood. We use a network representation of diffusion imaging data to show that white matter connectivity becomes increasingly optimized for a diverse range of predicted dynamics in development. Such optimized topologies emerge across 882 youth from ages 8 to 22 evidencing increasing local specialization. Notably, stable controllers in subcortical areas are negatively related to cognitive performance. Seeking to investigate structural mechanisms that support these changes, we simulate network evolution with a set of growth rules, to find that all brain networks - from child to adult - are structured in a manner highly optimized for network control. We further observe differences in the predicted control mechanisms of the child and adult brains, suggesting that the white matter architecture in children has a greater potential to increasingly support brain state transitions, potentially underlying cognitive switching. This work suggests mechanisms for the propagation and stabilization of brain activity at various spatial scales, revealing a possible mechanism of human brain development that preferentially optimizes dynamic network control over static features of network architecture.

2

Contributed Talk (Wednesday)

Persistent structures and piecewise isometries in 3D mixing systems*Paul Umbanhowar, Zafir Zaman, Menqi Yu, Paul Park, Julio Ottino and Richard Lueptow*Presenter: *Paul Umbanhowar / Northwestern University*

Chaotic dynamics has been shown to play a major role in fluid mixing, but the study of its relevance to solids mixing has only recently begun. We utilize a simple 3D geometry, a half-filled spherical tumbler rotated alternately by $\leq 90^\circ$ about two perpendicular horizontal axes, to develop a dynamical systems framework for solids mixing and non-mixing. In these systems, mixing can only occur during flow (from stretching due to shear and from collisional diffusion in the thin flowing layer) or by material separation intrinsic to the rotation protocol resulting from cutting and shuffling. In X-ray subsurface visualization experiments, surprisingly persistent ($O(100)$ iterations) non-mixing islands and larger non-mixing barriers occur. The geometric skeleton of the structures results from the subtle interplay between fluid-like mixing by stretching-and-folding, which can be modeled as a continuum flow, and solids mixing by cutting-and-shuffling, which is described by an idealized theoretical model (with an infinitely thin flowing layer) based on the mathematics of piecewise isometries. In these models, the stretching in the flowing layer vanishes as the flowing layer thickness decreases to reveal the underlying skeleton of the mixing. This dynamical systems perspective provides insight into the synergy of simultaneous fluid and solid mixing leading to a more fundamental understanding of mixing with both solid and flowing regions. Funded by NSF Grant #CMMI-1435065.

3

Invited Talk (Wednesday)

Dynamic Instabilities in Dislocation-Enabled Plasticity*James Langer*Presenter: *James Langer / University of California Santa Barbara*

For over half a century, dislocation theories of plasticity have been largely phenomenological; they have not been able to provide predictive first-principles explanations of basic phenomena such as strain hardening or brittle failure. In this talk, I will summarize the main features of a new statistical thermodynamic theory of dislocation-enabled plasticity. This theory now seems to be addressing many of the the central issues successfully. If time permits, I will show how it predicts the runaway shear banding instabilities that are observed experimentally.

4

Ignite Talk Session A (Wednesday) | Poster Session A (Wednesday)

Direct and Indirect Effects of Topography on the Dynamics of Mesoscale Eddies.*Larry Gulliver, Timour Radko and Justin Brown*Presenter: *Larry Gulliver / Naval Postgraduate School*

This study is focused on the equilibration of baroclinic instability which commonly develops in large-scale stratified oceanic flows, resulting in an active field of mesoscale eddies: large pockets of ocean which have different thermal, directional and density characteristics than the surrounding ocean water. In particular, we investigate how the transport characteristics of these instability-driven mesoscale flows are effected by (i) variation in topography, (ii) the orientation of the large-scale current, and (iii) structure of the basic velocity. In order to accomplish this, we simulate a zonal flow in a large-scale ocean basin using the Massachusetts Institute of Technology general circulation model (MITgcm). We then compare the lateral transport of these simulations with our analytic model, which is based on balancing the growth rate of the baroclinic instability derived from linear theory with that of a numerically derived secondary instability. Additionally, two flow regimes are considered; the first is an "indirect" scenario in which the current is spatially separated from the ocean floor and therefore any effects of topography on the flow are fundamentally eddy-induced. The second case is a "direct" one in which the current is in direct contact with the ocean bottom resulting in heightened sensitivity of the flow to these same topographic variations.

5

Ignite Talk Session A (Wednesday)

Quantum Chaos in Clifford Circuits*Michael Walter, Jordan Cotler, Sepehr Nezami and Brian Swingle*Presenter: *Michael Walter / Stanford University*

Strongly interacting quantum many-body systems are typically efficient scramblers of quantum information. Scrambling describes a process in which initially localized information is spread over the degrees of freedom of a system and rendered inaccessible to local measurements. It is an important part of the approach to thermal equilibrium in quantum many-body systems, and there has been much recent interest motivated by

the strongly chaotic properties of black holes in Anti-de Sitter space, as described by the AdS/CFT correspondence. To fully understand the various time scales involved in chaos and scrambling, it is essential to study tractable model systems of quantum many-body chaos. In this work, we study a model of a quantum dynamics generated by quantum circuits known as Clifford circuits. We show how a wide variety of measures of chaos, from the scrambling time to information-theoretic measures to level-spacing statistics, can be related to the orbit structure of a classical dynamics on an auxiliary discrete phase space. Using this quantum/classical dictionary, we make a detailed numerical study of the chaotic properties of several classes of Clifford circuits. We find that the phase space dynamics is generically as chaotic as the symmetries allow. Furthermore, we numerically study simple perturbations of Clifford circuits for small system sizes. We find that the perturbed Clifford circuits are typically strongly chaotic, even for weak perturbations that are by themselves very far from chaotic. The Clifford circuit model thus provides a tractable setting in which quantum chaos can be analyzed across a wide variety of time-scales and a starting point to analyze fully chaotic quantum circuit models. Our model provides a window onto a relatively unexplored area of many-body chaos, an area distinct from time-independent Hamiltonian models and random circuit models. No prior knowledge of quantum mechanics will be assumed.

6

Ignite Talk Session A (Wednesday)
**Tangled up in Blue: High Frequency Intermittent FPU
 Dynamics at Equilibrium**

David Campbell, Carlo Danieli and Sergej Flach

Presenter: *David Campbell | Boston University*

The equilibrium value of an observable defines a manifold in the phase space of an ergodic and equipartitioned many-body system. A typical trajectory pierces that manifold infinitely often as time goes to infinity. We use these piercings to measure both the relaxation time of the lowest frequency eigenmode of the Fermi-Pasta-Ulam chain, as well as the fluctuations of the subsequent dynamics in equilibrium. We show that previously obtained scaling laws for equipartition times are modified at low energy density due to an unexpected slowing down of the relaxation. The dynamics in equilibrium is characterized by a power-law distribution of excursion times far off equilibrium, with diverging variance. The long excursions arise from sticky dynamics close to regular orbits in the phase space. Our method is generalizable to large classes of many-body systems.

7

Ignite Talk Session A (Wednesday)
**Numerical Simulations of Oscillation-Driven Regolith
 Motion on Asteroids**

*Ronald Ballouz, Clara Maurel, Derek Richardson, Patrick Michel
 and Steve Schwartz*

Presenter: *Ronald Ballouz | University of Maryland College Park*

Many if not most small asteroids are covered by regolith, and small perturbations may be enough to disturb their surfaces in complex ways due to microgravity. Experiments to study low-gravity regolith dynamics are challenging, and properly validated numerical simulations can provide valuable insights. In this paper, we investigate numerically size segregation among regolith grains, which is likely to occur after repeated

shaking events. In particular, we are interested in the so-called Brazil-nut effect (BNE), i.e., the migration of a large intruder toward the top of a vertically shaken granular system. We go a step forward in simulating this effect by implementing horizontal periodic boundary conditions (PBC) in the N-body code `pkdgrav`, with the aim of making the simulations more representative of the expected asteroid environment. We study the influence of PBC on the BNE and compare them to cases with a confining boundary, in both Earth and low-gravity environments. We also investigate the influence of static and rolling friction on the BNE. With confining walls, we observe the well-known convection mechanism driving the BNE. However, we find that a different mechanism, consisting of void filling, is responsible for the BNE with PBC, and we discuss its relevance in light of previous studies. By running simulations in low-gravity, we show that this void-filling mechanism remains relevant in an asteroid environment. However, we find that depending on the gravity level, the void-filling mechanism is differently influenced by the friction properties of particles. We speculate this is likely due to a change in the granular flow timescales.

8

Ignite Talk Session A (Wednesday) | Poster Session A
 (Wednesday)

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

Bolun Chen, Jan Engelbrecht and Renato Mirollo

Presenter: *Bolun Chen | Boston College*

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

9

Ignite Talk Session A (Wednesday)
The onset of chaos in orbital pilot-wave dynamics
*Anand Oza, Lucas Tambasco, Daniel Harris, Rodolfo Rosales and
 John Bush*

Presenter: *Anand Oza | Courant Institute of Mathematical
 Sciences*

In a remarkable series of experiments, Yves Couder, Emmanuel Fort and coworkers showed that millimetric droplets bouncing on a vertically vibrating fluid bath exhibit phenomena previously thought to be exclusive to the microscopic quantum realm. We present the results of a numerical investigation of the emergence of chaos in a droplet's orbital dynamics when acted upon by one of the three different external forces, specifically, Coriolis, Coulomb, or linear spring forces. We

model the droplet as a continuous moving source of standing waves and derive an integro-differential trajectory equation for its dynamics. As the vibrational forcing of the bath is increased progressively, our theory predicts that circular orbits destabilize into wobbling orbits and eventually chaotic trajectories. We demonstrate that the route to chaos depends on the form of the external force. When acted upon by Coriolis or Coulomb forces, the droplet's orbital motion becomes chaotic through a period-doubling cascade. In the presence of a central harmonic potential, the transition to chaos follows a path reminiscent of the Ruelle-Takens-Newhouse scenario.

10

Ignite Talk Session A (Wednesday) | Poster Session A
(Wednesday)

Observing Chaos When the Dynamics of the System is Unknown: A Reservoir Computing Approach

Jaideep Pathak, Zhixin Lu, Brian Hunt, Michelle Girvan, Roger Brockett and Edward Ott

Presenter: *Jaideep Pathak | University of Maryland College Park*

A classical problem [1] of great practical utility is that of deducing the state of a dynamical system as a function of time from a limited number of concurrent system measurements. A scheme that accomplishes this is called an 'observer'. Construction of such schemes has mainly been limited to the case in which a model of the system is available. Observers have applications in control and prediction of dynamical systems. We consider the case where a model of the system is unavailable. We propose a solution to the problem of model-free nonlinear observation of dynamical systems using networks of neuron-like units known as Reservoir Computers [2]. The network is trained using multivariate time series data from a dynamical system without any knowledge of the equations governing the dynamics of the system. The trained network then acts as a nonlinear observer which is capable of reconstructing the full system state evolution from limited concurrent measurements of the system. We demonstrate our approach using the Rossler model and the Lorenz '63 model. The latter system highlights the issue of 'observability' in nonlinear systems [3] (see [1] for the linear case originally analyzed by Kalman). Subject to the condition of observability, we show that the Reservoir Computer observer can reconstruct the full set of dynamical system variables in both of these systems from measurement of a single scalar time series. We further show that this technique can be used to reconstruct the state evolution of spatiotemporal chaotic dynamical systems by demonstrating its effectiveness on the Kuramoto-Sivashinsky equation. In this spatiotemporal system we show that we can accurately reconstruct the full system state by using measurements of the time series at only two points in space. [Work supported by the U.S. Army Research Office, Grant W911NF-12-1-0101.]

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11

Ignite Talk Session A (Wednesday) | Poster Session A
(Wednesday)

State-dependent intrinsic predictability of cortical network dynamics

Leila Fakhraei, Shree Hari Gautam and Woodrow Shew

Presenter: *Leila Fakhraei | University of Arkansas*

The information encoded in cortical circuit dynamics is fleeting, changing from moment to moment as new input arrives and ongoing intracortical interactions progress. A combination of deterministic and stochastic biophysical mechanisms governs how cortical dynamics at one moment evolve from cortical dynamics in recently preceding moments. Such temporal continuity of cortical dynamics is fundamental to many aspects of cortex function but is not well understood. Here we study temporal continuity by attempting to predict cortical population dynamics (multisite local field potential) based on its own recent history in somatosensory cortex of anesthetized rats and in a computational network-level model. We found that the intrinsic predictability of cortical dynamics was dependent on multiple factors including cortical state, synaptic inhibition, and how far into the future the prediction extends. By pharmacologically tuning synaptic inhibition, we obtained a continuum of cortical states with asynchronous population activity at one extreme and stronger, spatially extended synchrony at the other extreme. Intermediate between these extremes we observed evidence for a special regime of population dynamics called criticality. Predictability of the near future (10-100 ms) increased as the cortical state was tuned from asynchronous to synchronous. Surprisingly, predictability of the more distant future (>1 s) was highest for asynchronous states. These experimental results were confirmed in a computational network model of spiking excitatory and inhibitory neurons. Our findings demonstrate that determinism and predictability of network dynamics depend on cortical state and the time-scale of the dynamics.

12

Ignite Talk Session A (Wednesday) | Poster Session A
(Wednesday)

Using data-driven models of brain function to predict individual differences in cognitive task performance

Kanika Bansal, John Medaglia, Danielle Bassett, Jean Vettel and Sarah Muldoon

Presenter: *Kanika Bansal | University at Buffalo, SUNY, Buffalo, NY*

Diffusion weighted imaging (dMRI) provides information about the structural connectivity between the regions of our brain, and this data provides a fundamental basis for efforts aimed at enhancing our understanding of the organization of the human brain as a complex and efficient network. How important is this basic structural skeleton of the brain in explaining and predicting individual differences in cognition? To address this question, we use a computational model that combines data-driven structural connectivity with nonlinear Wilson-Cowan oscillators to represent the spatiotemporal dynamics of a human brain. Motivated by previously collected experimental data, we target the left inferior frontal gyrus for stimulation and computationally investigate the differential activation of language and/or number subnetworks involved in three simple cognitive tasks across a cohort of individuals. We construct functional measures to separate the activation patterns of different individuals and find that our computational results can account for between-subject variability in experimental task performance. By emphasizing differences in the underlying structural connectivity, our results indicate that this relatively simple model provides a

powerful tool to differentiate the performances of individuals on basic cognitive tasks.

13

Ignite Talk Session A (Wednesday) | Poster Session A
(Wednesday)

Sub-threshold resonance facilitates sequential learning in biophysical neural networks.

James Roach and Michal Zochowski

Presenter: *James Roach* | *University of Michigan*

Oscillations in electrical activity are the hallmarks of information processing within the brain. A huge catalog of experimental evidence has shown that coordination of oscillations across and within brain areas is critical for learning and performance in memory tasks. While a large amount of work has focused on the generation of neural oscillations, the effect that these oscillations have on the spiking activity of neural populations is still not clear. Furthermore the extent to which these rhythms have a direct role in the learning process has not been evaluated. In the present work we propose that sub-threshold resonance, a dynamic property of single neurons, interacts to oscillating input to ensure that populations of neurons properly encode information within the strengths of recurrent connections. We demonstrate using a biophysical model that when individual cells display an input-current dependent shift in their resonance response, populations will arrange their phases to represent the differences in their input magnitudes. A natural consequence of how these networks learn while in resonance is that the strength of connections saturate when the network has successfully learned. Additionally we show that by selectively bringing subgroups of neurons into and out of resonance with an oscillating input allows networks to accurately store and reproduce sequences of activation. The results of our model reproduce experimental findings showing that the phase relationships between individual neurons and neural oscillations change during learning and recall. We argue that sub-threshold resonance paired with coordinated oscillations in neural activity provide a mechanism to accurately encode and retrieve information without over-strengthening connections between neurons. Altogether, we show that pattern storage and reproduction is an emergent property of networks arising from basic physical properties of individual neurons.

14

Invited Talk (Wednesday)

Simulating Granular Dynamics in Very Low Gravity

Derek Richardson, Ronald Ballouz, Joe DeMartini, A.M. Leisner Jr., Yang Lu, Clara Maurel, Patrick Michel, D.J. Robinson

Presenter: *Derek Richardson* | *University of Maryland College Park*

The study of granular dynamics is important in planetary science due to the ubiquity of particulate materials on celestial bodies, but is challenging because the principal driving force of the dynamics---gravity---can be very different from our terrestrial experience. Generally these processes on other worlds also take place at vastly different atmospheric pressure, often zero. Observations of small, airless solar system bodies such as asteroids and comets show evidence of surface landslides and size sorting, including loss or redistribution of fines, perhaps due to seismic shaking, electrostatic forces, or a combination of factors. Space agencies and commercial enterprises show increasing interest in visiting, landing on, and

sampling from such bodies, whose surfaces tend to be covered deeply in particulate materials (regolith) with largely unknown properties. Due to the difficulty and expense of carrying out experiments at very low gravity, we turn to computer simulations of granular dynamics to provide insight into the conditions that missions to other worlds may encounter and to help interpret observations of these bodies. As high-end computing resources become more readily available, granular dynamics simulations have become more sophisticated, treating particle collisions as finite-duration, multi-contact events with explicit friction forces between irregularly shaped grains subject to external forces, boundary conditions, and cohesion. It is imperative that such simulation methods be calibrated and validated at laboratory scales to give confidence in their application to other environments. Here I review our group's approach to simulating granular dynamics in very low gravity, with examples that include impacts into granular materials, vibration-induced segregation, landslides, models of samplers and landers, and, on larger scales, simulations of entire granular bodies (rubble piles) and planetary rings.

15

Contributed Talk (Wednesday)

Specific Transfer Entropy and Its Estimation from Empirical Data

David Darmon, Christopher Cellucci and Paul Rapp

Presenter: *David Darmon* | *Uniformed Services University*

Since its original formulation by Thomas Schreiber in 2000, transfer entropy has become an invaluable framework in the toolbox of nonlinear dynamicists working with empirical data. Transfer entropy and its generalizations provide a precise definition of uncertainty and information transfer that are central to the coupled systems studied in nonlinear science. In empirical applications, a central problem becomes the estimation of transfer entropy from the data on hand. The Kraskov-Stögbauer-Grassberger (KSG) formulation of k-th Nearest Neighbor estimators is still the state of the art for estimating transfer entropy from coupled systems with continuous states. However, the KSG formulation relies on many tuning parameters that are either determined heuristically or sidestepped with deference to asymptotics. By formulating the computation of transfer entropy directly as a nonparametric model selection and estimation problem, we replace these heuristics with statistically principled procedures. In addition, our formulation, unlike the k-th Nearest Neighbor approaches, allows for the computation of a state-specific transfer entropy. This specific transfer entropy makes possible a time-resolved analysis of the predictive impact of a candidate input system on a candidate output system. We demonstrate the utility of specific transfer entropy and our proposed estimation procedure with both discrete-time and continuous-time model systems. We show that our estimator for specific transfer entropy outperforms KSG-like estimators in elucidating the time-resolved transfer of information.

16

Contributed Talk (Wednesday)

A network approach to pattern formation in atmospheric cloud fields

Franziska Glassmeier and Graham Feingold

Presenter: *Franziska Glassmeier* | *NOAA Boulder*

Clouds reflect incoming sunlight back to space and thus play an important role in modulating energy flows in the climate system. The representation of organized shallow clouds, in particular, is one of the largest uncertainties in current climate models. Organized fields of shallow clouds are the result of Rayleigh-Bénard convection in moist atmospheric air. In the absence of rain, such cloud fields are arranged in a relatively regular pattern of cloudy cells separated by cloud-free rings of downwelling air ('closed cells'). Raining cloud fields, in contrast, exhibit an oscillating pattern of cloudy rings surrounding cloud free cells of negatively buoyant air caused by sedimentation and evaporation of rain ('open cells'). Despite their practical relevance, the structure of open and closed cellular cloud fields has not been studied in detail. In this contribution, we approach their organization from the perspective of a 2-dimensional cellular network. Our characterization of cloud networks is based on large-eddy simulations with detailed cloud physics. We find that cellular networks derived from open- and closed-cell simulations are almost indistinguishable: The distributions of nearest neighbors, or cell degree, are centered at 6 with a standard deviation of 1 such that the cellular patterns are approximately hexagonal. The average degree of 6 follows from the Euler formula because cloud networks feature triple junctions. The degree of individual cells is found to be proportional to the normalized size of the cells (Lewis law) with a proportionality constant of 0.2 for both cell types. The arrangement of cells favors the neighborhood of large (high-degree) and small (low-degree) cells and obeys the Aboave-Weaire law with a common parameter value of 0.9. The fulfillment of these two laws indicates a maximization of the system's entropy and the absence of specific constraints that could reduce the network's randomness. We show that the macroscopic network properties emerge independent of the state of the cloud field because the differing microscopic processes governing the evolution of closed as compared to open cells correspond to topologically equivalent network dynamics: Open and closed cell dynamics can both be mimicked by versions of cell division and cell disappearance and are biased towards the expansion of smaller cells.

17

Poster Session A (Wednesday)

The Time Delayed Ensemble Kalman filter for nonlinear Estimation

Zhe An and Henry Abarbanel

Presenter: *Zhe An* | University of California San Diego

Optimal nudging method based on time-delayed embedding theory has shown potentials on analyzing and data assimilation in previous literature. To extend the application and promote the practical implementation, new assimilation method based on the time delayed embedding space is presented and the connection with other standard assimilation methods (4D variational analysis, Ensemble Kalman Filter) are studied. Results show the standard data assimilation method incorporating information from the time series of data can reduce the sufficient observation needed to preserve the quality of numerical prediction, making it a potential alternative in the field of data assimilation of large geophysical models.

18

Poster Session A (Wednesday)

Nonlinear Dynamics of Macroscopic Quantum Superconducting Metamaterials

Steven Anlage, Daimeng Zhang, Melissa Trepanier, Edward Ott and Thomas Antonsen

Presenter: *Steven Anlage* | University of Maryland College Park

Through experiments, numerical simulations, and theory we explore the behavior of 2D rf SQUID (radiofrequency superconducting quantum interference device) metamaterials, which show extreme tunability and nonlinearity. The emergent properties are sensitive to the degree of coherent response of the driven metamaterial. Coherence suffers in the presence of disorder, which is experimentally found to be mainly due to a dc flux gradient. We investigate methods to recover the coherence, specifically by varying the coupling between the SQUID meta-atoms and reducing the SQUID tunability. We also investigate the SQUID metamaterial as a nonlinear medium through detailed two-tone intermodulation (IM) measurement over a broad range of tone frequencies and tone powers. The response of nonlinear metamaterials and superconducting electronics to two-tone excitation is critical for understanding their use as low-noise amplifiers and tunable filters, for example. A sharp onset followed by a surprising strongly suppressed IM region near the resonance is observed. Using a two time scale analysis technique, we present an analytical theory that successfully explains our experimental observations. The theory predicts that the IM can be manipulated with tone power, center frequency, frequency difference between the two tones, and temperature. This quantitative understanding potentially allows for the design of rf-SQUID metamaterials with either very low or very high IM response.

See <https://arxiv.org/abs/1606.09234>.

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Poster Session A (Wednesday)

Hidden Structures of Information Transport Underlying Spiral Wave Dynamics

Hiroshi Ashikaga and Ryan James

Presenter: *Hiroshi Ashikaga* | Johns Hopkins University

Spiral waves are a macro-scale dynamics of excitable media that plays an important role in physical, chemical and biological systems, including the Belousov-Zhabotinsky reaction, seizures in the brain, and lethal arrhythmia in the heart. Spiral wave dynamics can exhibit a wide spectrum of behaviors. For example, a spiral wave can be stationary or drifting. A spiral wave can exist alone, or coexist with other spiral waves. A single spiral wave can also break up into multiple spiral waves. These behaviors make visual identification of spiral waves extremely challenging. This may have contributed to disappointing results of interventional catheter ablation therapy to target spiral waves to cure cardiac arrhythmia in clinical settings. Therefore, it is critically important to develop a method for quantitative assessment of spiral wave dynamics that is stable over the wide spectrum of behaviors. A traditional method to quantify spiral wave dynamics is to use rotor dynamics as a surrogate. The rotor of a spiral wave can be defined as a phase singularity within a phase map. However, the relationship between rotors and spiral waves is not one-to-one: phase mapping tends to identify rotors where there is no spiral wave, whereas some spiral waves can have no rotors. Here we present a hybrid geometric and information-theoretic approach to quantifying spiral wave dynamics as a macro-scale behavior of excitable media. Information theory is one of the predominant mathematical paradigms for studying a system's multi-scale structure. In essence, we view excitable media as a

communication system where components share and/or transfer information with their nearest neighbors, and reduce the wide spectrum of spiral wave behaviors to information transport which can be quantified as a surrogate for spiral wave dynamics. To define information transport in this system, we combine an information-theoretic measure of information flow with the geometry of the excitable medium leading to an information velocity at each component. Similar to an electrical test particle, we define an information test particle - a point of negligible properties other than to be influenced by the field - as a point that moves with the local information velocity. We then calculate the trajectory of information particles to derive coherent structures over the observation time period. Our approach is computationally efficient in many excitable media of interest. We demonstrate the effectiveness of our approach by applying it to numerical examples of an excitable medium with different numbers and spatial patterns of spiral waves.

Presenter: *Tyrus Berry / George Mason University*

Methods of data assimilation are established in physical sciences and engineering for the merging of observed data with dynamical models. When the model is nonlinear, methods such as the ensemble Kalman filter have been developed for this purpose. At the other end of the spectrum, when a model is not known, the delay coordinate method introduced by Takens has been used to reconstruct nonlinear dynamics. In this article, we merge these two important lines of research. A model-free filter is introduced based on the filtering equations of Kalman and the data-driven modeling of Takens. This procedure replaces the model with dynamics reconstructed from delay coordinates, while using the Kalman update formulation to reconcile new observations. We find that this combination of approaches results in comparable efficiency to parametric methods in identifying underlying dynamics, and may actually be superior in cases of model error.

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Ignite Talk Session A (Wednesday) | Poster Session A
(Wednesday)

Using data-driven models of brain function to predict individual differences in cognitive task performance

Kanika Bansal, John Medaglia, Danielle Bassett, Jean Vettel and Sarah Muldoon

Presenter: *Kanika Bansal / University at Buffalo, SUNY, Buffalo, NY*

See Abstract 12

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Poster Session A (Wednesday)

A Simple approach of Destriping Remote Sensing Imagery

Ranil Basnayake, Erik Bollt, Nick Tufillaro and Jie Sun

Presenter: *Ranil Basnayake / Clarkson University*

Striping is a commonly pronounced artifact in many remote sensing (satellite) images such as images from Visible Infrared Imaging Radiometer Suite (VIIRS) and Hyperspectral Imager for the Coastal Ocean (HICO). These striping patterns are occurred mainly due to the variations of calibrations, sensor arrangement and the view angles from detector to detector. It is an important step to remove these striping patterns as they affect not only the visual appearance but also classification and quantitative applications. In this framework, we develop a destriping approach to smooth the noisy data transverse to the stripes, while preserving the original features of the image. The destriped image can be obtained by either solving the problem as a variational model or a statistical inversion model

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Poster Session A (Wednesday)

Ensemble Kalman filtering without a model

Franz Hamilton, Tyrus Berry and Timothy Sauer

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Poster Session A (Wednesday)

Chaotic Time Series Prediction with FPGA-Based Reservoir Computers

Daniel Canaday, Aaron Griffith and Daniel Gauthier

Presenter: *Daniel Canaday / Ohio State University, Department of Physics*

In recent years, the reservoir computing paradigm has demonstrated state-of-the-art performance in a number of benchmark machine-learning tasks while maintaining their remarkably low training time. Advances in the performance of field-programmable gate arrays (FPGAs) have allowed for high-performance hardware implementations of reservoir computing. Whereas most groups have been interested in operating reservoir computers in discrete time, we explore the implications of letting the reservoir run autonomously, with continuous-time dynamics. We implement a Boolean, continuous-time reservoir computer on an FPGA and train the network to predict the Mackey-Glass time series. We find that a Boolean, continuous-time network of 200 nodes is able to achieve a normalized root-mean-square error of less than 0.05 over 100 predictive time-steps, whereas a simulated Boolean, discrete-time network of the same size is essentially unable to learn the series at all.

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Ignite Talk Session A (Wednesday) | Poster Session A
(Wednesday)

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

Bolun Chen, Jan Engelbrecht and Renato Mirollo

Presenter: *Bolun Chen / Boston College*

See Abstract 8

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Poster Session A (Wednesday)
Nonlinear Dynamics in Optimal Communication Waveforms

Ned Corron and Jonathan Blakely

Presenter: *Ned Corron / US Army AMRDEC*

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

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Poster Session A (Wednesday)
Lagrangian descriptors of time-dependent transition states

Galen Craven

Presenter: *Galen Craven / University of Pennsylvania*

The persistence of a transition state structure in systems driven by time-dependent environments allows the application of modern reaction rate theories to describe nonequilibrium chemical kinetics. Identifying this structure is problematic, however, in driven systems and has previously been limited by theories built on perturbative expansion about a saddle point. Recently, it has been shown that to obtain formally exact rates in chemical reactions that are induced by thermal fluctuations and nonequilibrium forces, a transition state trajectory must be constructed. In this talk, I will show how this distinguished trajectory can be obtained directly using the method of Lagrangian descriptors (LD) [G. T. Craven and R. Hernandez, Phys. Rev. Lett., 115, 148301 (2015)], which are geometrical observables that arise in trajectory-based descriptions of the reaction dynamics. The general formulation of LD will be discussed and subsequently applied in order to construct the transition state trajectory and the associated moving reaction manifolds on model energy surfaces subject to various driving and dissipative conditions. Application of the presented methodology allows the reactive flux (and hence the classical reaction rate) to be determined exactly in chemical reactions that occur in nonequilibrium environments.

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Poster Session A (Wednesday)
Transport, Diffusion, and Energy in the Arnold-Beltrami-Childress map

Swetamber Das and Neelima Gupte

Presenter: *Swetamber Das / Indian Institute of Technology Madras*

We study the transport and diffusion properties of passive inertial particles described by a six-dimensional dissipative bailout embedding map. The base map chosen for the study is the three dimensional incompressible Arnold-Beltrami-Childress (ABC) map (Eq. 1) as a representation of volume preserving flows. There are two distinguishable cases: the two-action and the one-action cases, depending on whether two or one of the parameters (A;B;C) exceed 1 in the following map.

$$\left. \begin{aligned} x_{n+1} &= x_n + A \sin(z_n) + C \cos(y_n) \\ y_{n+1} &= y_n + B \sin(x_{n+1}) + A \cos(z_n) \\ z_{n+1} &= z_n + C \sin(y_{n+1}) + B \cos(x_{n+1}) \end{aligned} \right\} \bmod 2\pi$$

The dynamics is governed by parameters (α, γ) which quantify the mass density ratio and dissipation respectively. There are important differences between the aerosol ($\alpha < 1$) and the bubble ($\alpha > 1$) regimes. We have studied the diffusive behavior of the system and constructed the phase diagram in the parameter space by computing diffusion exponents. Three classes have been broadly classified - subdiffusive transport ($\eta < 1$), normal diffusion ($\eta \approx 1$), and superdiffusion ($\eta > 1$) with $\eta \approx 2$ referred to as the ballistic regime. Correlating the diffusive phase diagram with the phase diagram for dynamical regimes seen earlier [1], we find that the hyperchaotic bubble regime is largely correlated with normal and superdiffusive behavior. In contrast, in the aerosol regime, ballistic superdiffusion is seen in regions which largely show periodic dynamical behaviors whereas subdiffusive behavior is seen in both periodic and chaotic regimes. The probability distributions of the diffusion exponents show power law scaling for both aerosol and bubbles in the superdiffusive regimes. We further study the Poincaré recurrence times statistics of the system. Here, we find that recurrence time distributions show power law regimes due to the existence of partial barriers to transport. Moreover, the plot of the average kinetic energies of particles versus the mass density ratio for the two-action case exhibits a Devil's staircase-like structure for higher dissipation values. We explain these results and discuss their implications for realistic systems.

[1] Swetamber Das and Neelima Gupte. Dynamics of impurities in a three-dimensional volume-preserving map. Phys. Rev. E, 90:012906, 2014.

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Ignite Talk Session A (Wednesday) | Poster Session A (Wednesday)
State-dependent intrinsic predictability of cortical network dynamics

Leila Fakhraei, Shree Hari Gautam and Woodrow Shew

Presenter: *Leila Fakhraei / University of Arkansas*

See Abstract 11

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Poster Session A (Wednesday)
Experimental Study of Quantum Graphs With and Without Time-Reversal Invariance

Ziyuan Fu, Trystan Koch, Thomas Antonsen, Edward Ott and Steven Anlage

Presenter: *Ziyuan Fu / University of Maryland College Park*

An experimental setup consisting of a microwave network is used to simulate quantum graphs. The random coupling model (RCM) is applied to describe the universal statistical properties of the system with and without time-reversal invariance. The networks which are large compared to the wavelength, are constructed from coaxial cables connected by T junctions, and

by making nodes with circulators time-reversal invariance for microwave propagation in the networks can be broken. The results of experimental study of microwave networks with and without time-reversal invariance are presented both in frequency domain and time domain. With the measured S-parameter data of two-port networks, the impedance statistics and the nearest-neighbor spacing statistics are examined. Moreover, the experiments of time reversal mirrors for networks demonstrate that the reconstruction quality can be used to quantify the degree of the time-reversal invariance for wave propagation. Numerical models of networks are also presented to verify the time domain experiments.

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Poster Session A (Wednesday)

Perron-Frobenius meet Monge-Kantorovich: A set-oriented graph-based approach to optimal transport

Piyush Grover and Karthik Elamvazhuthi

Presenter: *Piyush Grover / Mitsubishi Electric Research Labs*

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

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Ignite Talk Session A (Wednesday) | Poster Session A (Wednesday)

Direct and Indirect Effects of Topography on the Dynamics of Mesoscale Eddies.

Larry Gulliver, Timour Radko and Justin Brown

Presenter: *Larry Gulliver / Naval Postgraduate School*

See Abstract 4

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Poster Session A (Wednesday)

Implementation of a Chaotic Equation in High Speed Electronics

Chase Harrison, Benjamin Rhea, Frank Werner and Robert Dean

Presenter: *Chase Harrison / Auburn University*

Chaotic systems have many inherent characteristics that can be beneficial in electronic applications. Some of these notable characteristics include continuous power spectral density, long-term aperiodicity, and sensitivity to initial conditions, which is advantageous in communication and radar systems, as well as in random number generation. There are many different types of ideal nonlinear differential equations that can exhibit chaotic behavior over a wide range of parameters. However, many of these equations are mathematically defined using nonlinearities that may not lend themselves to electronic implementation. For this reason, the choice of the nonlinearity must be considered for high-speed electronic implementation. Specifically, for random number generation, care must be taken to ensure that the hardware implementation of the chaotic system is at the highest frequency possible without destroying the integrity of the random signal or adding a bias due to the nonideal elements used to implement the governing equations. Moreover, equations that necessitate complex multifeedback paths can introduce noise, distortion or crosstalk in signal lines on a physical circuit board, which can compromise the system as a whole. Presented in this work is a high-speed electronic implementation of a chaotic system which very closely maintains the ideal dynamics of the original system.

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Poster Session A (Wednesday)

Dynamics of small networks of biomimetic artificial neurons

Harold Hastings, Oscar Hernandez, Lucy Jiang and Lindsey Tensen

Presenter: *Harold Hastings / Bard College at Simon's Rock and Hofstra University*

We describe experimental and simulation work on the dynamics of small networks of biomimetic artificial neurons, including the role of local dynamics, network topology, connection strength, heterogeneity and noise on synchronization. Models include Keener's and Maeda and Makino's "minimal" model circuits for FitzHugh-Nagumo neurons as well as the Belousov-Zhabotinsky chemical reaction, the prototype chemical oscillatory system. A wide variety of complex synchronization and emergent behavior is seen. We relate this work to results of Dr. Spano's group on analog integration of the FitzHugh-Nagumo equations and Dr. Fraden's group on diffusion coupled networks of Belousov-Zhabotinsky reaction "cells." There are potential applications to computer science, biology, and biomedicine.

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Poster Session A (Wednesday)

Invasion fronts in the Fisher-KPP equation on homogeneous trees and random graphs

Aaron Hoffman and Matt Holzer

Presenter: *Matt Holzer / George Mason University*

We study the dynamics of the Fisher-KPP equation on the infinite homogeneous tree and Erdos-Reyni random graphs. We assume initial data that is zero everywhere except at a single node. For the case of the homogeneous tree, the solution

will either form a traveling front or converge pointwise to zero. This dichotomy is determined by the linear spreading speed and we compute critical values of the diffusion parameter for which the spreading speed is zero and maximal and prove that the system is linearly determined. We also study the growth of the total population in the network and identify the exponential growth rate as a function of the diffusion constant. Finally, we make predictions for the Fisher-KPP equation on Erdos-Renyi random graphs based upon the results on the homogeneous tree. We observe that exponential growth rates on the random network can be bounded by growth rates on the homogeneous tree and provide an explanation for the sub-linear exponential growth rates that occur for small diffusion.

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Poster Session A (Wednesday)

Dynamic Diffraction Analysis of *C. elegans*

Miranda Hulsey-Vincent, Clara Alivisatos, Kathleen Susman and Jenny Magnes

Presenter: Miranda Hulsey-Vincent | Vassar College

Understanding the motion of living organisms informs on how organisms behave. *Caenorhabditis elegans* are model organisms for studying simplified nervous and musculoskeletal systems. This organism shares many cellular characteristics with humans and other more developed organisms, making these nematodes ideal study subjects in a variety of fields. One field of research aims to study the interaction between environmental stimuli and muscle movement to better understand how motion is effected in advanced organisms. However, current methods of motion analysis require time-consuming steps such as recording and processing video images to effectively trace two-dimensional motion. We are developing a method using light diffraction that will allow for time efficient three-dimensional tracking. Using a Helium Neon laser, optical set up, Picoscope digital oscilloscope, and frequency analyzer, we investigated the frequency of *C. elegans*' swimming motions using laser light diffraction and observed the resultant diffraction patterns. Our optical setup allowed for the time-varying diffraction patterns of a swimming worm to be observed on an amplified photodiode sensor. This signal was analyzed using the Picoscope. We collected voltage versus time graphs that in real-time reveal the dynamics of the worm's movement, especially the frequency of the motion. Specifically, we observed the thrashing frequency of OH7543 "rollers" *C. elegans*. This laser diffraction technique is different from other methods available to researchers who analyze microorganism motion. Further development of the technique would be beneficial for future research of worm motion and allow for a new type nematode identification process.

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Poster Session A (Wednesday)

Optimal target sets for a random walk on an undirected graph

Fern Hunt

Presenter: Fern Hunt | National Institute of Standards and Technology

We consider a standard random walk on an undirected graph $G=(V,E)$ and the optimization problem that arises from the search for the subset of vertices of G of fixed cardinality, that is the best target set or destination for random walkers starting outside the set. If we define a set function F for a subset of vertices A , as $F(A)$ = the sum of the expected first arrival times

of random walkers starting outside of A , then $F(A)$ is the smallest F value taken on by sets of the same cardinality as A . Posed as an optimization problem, finding an optimal A is probably NP complete. Fortunately, we can show that F is supermodular and monotone. We present a method for finding or approximating these sets that is based on restricting the search to optimal and near optimal sets. A submodular non-decreasing rank function is introduced that permits some comparison between the results of our method and the greedy algorithm-- a classical method for producing approximations. We show when our method is no worse than the greedy method and when it is an improvement. Knowledge of the curvature of F and the increments in the rank allow us to quantify the degree of improvement. Finally we show some intriguing connections between our problem and well known combinatorial problems such as the partial vector cover and maximum budget coverage problem.

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Poster Session A (Wednesday)

Coupled Autocatalytic Reactions: Interconversion and Extinction of Species

Aditi Khot and S Pushpavanam

Presenter: Aditi Khot | Indian Institute of Technology Madras

Autocatalysis or self-replication is an important phenomenon which arises across various disciplines like chemistry, ecology (animal reproduction), economics (sustained growth of goods and services), and biology (DNA replication). In the context of chemical reaction engineering, the dynamics of a single autocatalator in open and closed systems has been studied extensively. These autocatalytic reaction systems are non-linear and exhibit complex behavior like multiple steady states and oscillations. Coupled systems in which two species are produced autocatalytically are also found in the literature: Lotka-Volterra predator-prey equations, complementary metabolism, Hypercycles. In this work, we have analyzed another coupled autocatalytic system (1), where each species catalyzes the autocatalysis of the other species. Here, each species acts as a substrate and gets consumed in the autocatalysis. The system proposed here is comprised of two species- A and B , both undergoing autocatalysis. One undergoes cubic autocatalysis while the other quadratic autocatalysis. Further, the system is coupled as each species catalyzes the autocatalysis of the other. The asymmetry in this interconversion is introduced by the different order of the autocatalysis.

$$B + 2A \rightarrow 3A$$

$$A + B \rightarrow 2B \quad (1)$$

Model (1) can also capture interconversion of two isomers. It is distinct from asymmetric autocatalysis of enantiomers, where the substrate gets converted to an enantiomeric species in the enantiomer's presence. In our system there is no substrate but the isomers themselves get converted to each other. The model can also represent interconversion of two social groups. In this work, in addition to the two reactions in (1), uncatalyzed generation and decay of these species are included. We captured the non-linear behavior of this system by applying singularity theory and bifurcation theory. An important question we address is in a system where both species exist under what conditions will only one of the species remain. This situation corresponds to one social group becoming extinct by getting completely converted to the other. In a system of enantiomers reacting autocatalytically, it corresponds to conversion of a racemic mixture to a pure enantiomer. These conditions for complete conversion to single species were determined for all combinations of generation and decay

reactions. In this work an extensive analysis of the system has been performed by studying a total of twelve cases. The common features and dominant factors with respect to direction of conversion in the all the cases analyzed are determined.

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Poster Session A (Wednesday)

Using the permutation entropy to detect nonlinearity in short and noisy time series data

Luciano Zunino and Christopher Kulp

Presenter: *Christopher Kulp | Lycoming College*

In this poster we present a study demonstrating the effectiveness of the permutation entropy in detecting nonlinearity in time series data. The study is performed by comparing the permutation entropy of a model or experimental time series to the permutation entropy of an ensemble of surrogates. It is found that the permutation entropy is a robust discriminator of nonlinearity in short and noisy time series data.

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Poster Session A (Wednesday)

Relativistic quantum kicked rotor

Boon Leong Lan

Presenter: *Boon Leong Lan | Monash University*

The kicked rotor is a prototypical model in quantum chaos. The majority of the studies to date have only employed non-relativistic quantum mechanics, where the time evolution of the non-relativistic quantum wave packet is governed by a simple mapping for the coefficients in the free-rotor state expansion. Here, we present the corresponding relativistic quantum mapping, and some numerical results for the time evolution of the relativistic quantum wave packet and auto-correlation function.

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Poster Session A (Wednesday)

Collective cell migration over long time scales reveals distinct phenotypes

Rachel Lee, Christina Stuelten, Carole Parent and Wolfgang Losert

Presenter: *Rachel Lee | University of Maryland College Park*

During cancer progression, cells migrate away from the primary tumor to form clinically dangerous metastatic tumors. This migration behavior can encompass both the motion of single cells and collective cell groups. Although collective groups of cells are increasingly implicated as important during metastasis, less is known about the dynamics of interacting cells. Using cell lines which model cancer progression, we use time-lapse imaging and particle image velocimetry (PIV) to measure changes in collective behavior. We find differences in the migration of non-malignant MCF10A cells and malignant MCF10CA1a cells over multiple time scales. Using finite-time Lyapunov exponents (FTLE) and changes in FTLE values over time, we show that epithelial sheet behavior includes cooperative long-time dynamics that cannot be captured by short-time metrics such as instantaneous speed or directionality. The use of multiple migration metrics allows us

to more precisely investigate how the perturbation of cell-cell adhesion influences collective migration behavior in these two cell types.

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Poster Session A (Wednesday)

Analytic Solutions Throughout A Period Doubling Route to Chaos

Marko Milosavljevic, Jonathan Blakely and Ned Corron

Presenter: *Marko Milosavljevic | Charles M. Bowden Laboratory, Aviation and Missile Research, Development, and Engineering Center*

Nonlinear dynamical systems can rarely be solved analytically. Numerical approximations to solutions of nonlinear systems were essential to the work of pioneers such as Lorenz, Feigenbaum, and Rossler. So recent reports of chaotic dynamical systems with analytic solutions are quite surprising. We show how a simple modification of known solvable systems produces a classic nonlinear phenomenon hitherto unseen in any solvable system. Specifically, we introduce an analytically solvable hybrid dynamical system that exhibits a period doubling route to chaos. The map in this case is smooth allowing for a greater variety of nonlinear phenomena than previously studied solvable hybrid systems. The system contains both continuous and discrete time states that are coupled such that the values of a continuous time state at subsequent transition times of the discrete state are related by a one dimensional map. We present analytic solutions describing an entire period doubling route to chaos. We also describe an electronic experimental implementation of the system that shows a similar route to chaos. These examples demonstrate that a much greater variety of dynamics is possible in solvable hybrid systems than was previously expected.

42

Poster Session A (Wednesday)

Bayesian approach for information theory to explain temporal dynamic between stimuli in EEG/MEG signals

Carlos Mugruza-Vassallo

Presenter: *Carlos Mugruza-Vassallo | Universidad de Lima*

In a previous work, variation effects in stimulus properties and time between cue and target (CTOA), in auditory attention tasks were explored using recently developed approaches to EEG analysis including Linear Modeling (LIMO) and fMRI studies. (Mugruza-Vassallo, 2015). Here, bearing in mind recent schizophrenia analysis and a recent proposal to setup a better experiment for EEG analysis (Mugruza-Vassallo, in press), is presented another way to look at the results showing the effect of temporal processing between cues and stimuli maybe analysed as a function on the number of states present under basic simulations employing theory of information at low level on brain processing. The time constants found in MEG results (Lu, Williamson & Kaufman, 1992) and the CTOA to the analysis applied for EEG signal (Mugruza-Vassallo, 2015), both resulted in an information theory framework that was calculated now for schizophrenia patient results. Simulation considered a simple Bayesian approach and showed the information of the experiment, a saddle indentation in the curve of the information measure based on the states of the incoming signal at around 300 ms CTOA was found. It was argue how much can affect MMN and P300 signal. Results revealed differences for the waveforms of current condition by

depending on which condition appeared previously. This approach may allow to study better the relationships between CTOA, executive function and orienting of attention.

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Poster Session A (Wednesday)

Size-dependent properties of branching of tadpole-like Physarum plasmodium.

Mshahide Okada and Tatsunari Sakurai

Presenter: *Mshahide Okada* | Chiba University

The true slime mould *Physarum plasmodium* is a unicellular organism. It migrates with different size and shape. About 0.5 mm and less length, it takes circle-like shape and migrates randomly. About 0.5~1 mm length, it takes tadpole-like shape and migrates linearly and turns gradually. About 0.5~10 mm length, it often branches its frontal tip like Y or tree branch shape [1]. When its shape is like Y, one of these branched tips grows. And, when the Y shape organism changes migrating direction, it turns more sharply than the tadpole-like organism. In 10 mm and more length, it makes tube networks and gets some complex abilities like "Maze-solving [2]". We consider there are relations between the branching and the complex abilities. Increasing attention has been focused on size-dependent behavior of it. But the relationship is still open question. So, we particularly study the branching organism. In this study, we carried out experimentally about relations between volume and frequency, angle of branching in the organism. Experimental outline is as follows; (1) cutting off its body into about 0.5~1 mm length. (2) placing these bodys on 1 % agar sheet. (3) putting cover grass on their body with 100 μ m spacer. (4) estimating their area. (5) removing cover grass. (6) replacing these bodys on other agar. (7) observing their behavior for ten hours to few days. we found; (1) the branching is more often. (2) there are three kinds of the growing tip in branching. First, when the degree of one of the frontal tips to the moving direction is less than the other, the tip grows. Second, the other frontal tip grows. Last, these tips hardly ever grow up, then the *Physarum plasmodium* grows up their back edge like it went back. The probability of first, second, third is 60~70 %, 33%, 5% respectively. We would like to discuss the relations between the result and the complex abilities in this conference.

[1] "Allometry in *Physarum plasmodium* during free locomotion: size versus shape, speed and rhythm", Shigeru Kuroda et al. *Journal of Experimental Biology*, 218, 3729-3738, (2015).

[2] "Maze-solving by an amoeboid organism", T. Nakagaki And H. Yamada, *Nature*, 407, 470, (2000).

44

Poster Session A (Wednesday)

Observing Chaos When the Dynamics of the System is Unknown: A Reservoir Computing Approach

Jaideep Pathak, Zhixin Lu, Brian Hunt, Michelle Girvan, Roger Brockett and Edward Ott

Presenter: *Jaideep Pathak* | University of Maryland College Park

See Abstract 10

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Poster Session A (Wednesday)

Finding and Forming Synchronized Clusters in Complex Networks of Oscillators Using Symmetries

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

Presenter: *Louis Pecora* | Naval Research Laboratory

Many networks are observed to produce patterns of synchronized clusters, but it has been difficult to predict these clusters in large complex networks 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. In networks with Laplacian coupling clusters are possible which do not directly result from symmetries; however, it is possible to construct all possible synchronized clusters starting from the symmetry clusters.

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Poster Session A (Wednesday)

Symbolic template iterations of complex quadratic maps

Anca Radulescu and Ariel Pignatelli

Presenter: *Ariel Pignatelli* | State University of New York at New Paltz

The behavior of orbits for iterated polynomials has been widely studied since the dawn of discrete dynamics as a research field, in particular in the context of the complex quadratic family. While more recent research has been studying the orbit behavior if the map changes along with the iterations, many aspects of non-autonomous discrete dynamics remain largely unexplored. Our work is focused on studying the behavior of pairs of quadratic maps when iterated according to a rule prescribed by a binary template. We investigate how the traditional theory changes in these cases, illustrating in particular how the symbolic template can affect dynamics (behavior of orbits, topology of Julia and Mandelbrot sets). This is of potential interest to a variety of applications (including genetic and neural coding), since it investigates how an occasional or a reoccurring error in a replication or learning algorithm may affect the outcome.

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Poster Session A (Wednesday)

Real and complex behavior for networks of coupled logistic maps

Anca Radulescu and Ariel Pignatelli

Presenter: *Anca Radulescu* | SUNY New Paltz

Many natural systems are organized as networks, in which the nodes interact in a time-dependent fashion. The object of our study is to relate connectivity to temporal behavior in networks of logistic maps, coupled according to various connectivity schemes. While our previous work addressed primarily low-dimensional systems, we are currently studying the relationship between system architecture and dynamics in large networks of nodes. We consider extensions of the Julia and Mandelbrot sets traditionally defined for single map iterations. We use a combination of analytical and numerical tools to illustrate how topological properties of the Julia set change when altering the edge configuration of the network adjacency graph. We discuss the implications of extending Fatou-Julia theory from iterations of single maps, to iterations

of ensembles of maps coupled as nodes in a network. We discuss possible interpretations of our results in the context of feature sustainability in learning natural systems.

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Poster Session A (Wednesday)

Modelling paradoxical excitation under general anesthesia as an inverse response phenomenon

Aditi Khot, Roshan M. Regy and S Pushpavanam

Presenter: *Roshan M. Regy | Birla Institute of Technology and Science, Pilani- Goa`*

General anesthesia has been used during surgery to induce unconsciousness, analgesia and amnesia since the last century. The mechanism of these drugs is still not clearly understood. Electroencephalogram (EEG) is often used to provide insight about characteristics of anesthesia. EEG patterns have been studied to study their variations with anesthesia dosage and more specifically for the point of loss of consciousness and emergence. In the past decade, there has been interest in developing a theoretical understanding of how general anesthesia effects the functioning of brain. These theoretical studies have tried to reproduce the EEG patterns, leading to a better understanding of the cellular mechanism of general anesthesia. However, still a gap lies between the experimentally observed EEG patterns and the mathematical models developed. One important feature of EEG pattern under general anesthesia is 'paradoxical excitation'. At low dose of anesthesia, the power in beta frequency range of EEG increases, suggesting an increase in brain activity. This is contradictory to the effect anesthesia produces at a sedative dose and hence, is termed as 'paradoxical excitation'. In the past decade, several researchers have modeled this phenomenon of paradoxical excitation, using continuum models and network models to reproduce the anesthesia induced EEG pattern. In this work, we suggest an innovative approach for addressing this problem using concepts from dynamical systems. Here, we model the various processes occurring in the brain in the frame work of a process control with anesthesia concentration as input and EEG as output. The motivation for this approach stems from the 'inverse response' phenomena observed widely in chemical engineering processes. Inverse response occurs when the initial response of the system is in the direction opposite to that of the final response. This phenomenon has been observed in systems like boilers and distillation columns, and results from two opposite effects acting at different time scales. These systems have been modeled using process control loops and are well understood in literature. Using this approach the EEG response of brain is modeled as a control process. This will help us identify the key processes which play an important role in 'paradoxical excitation' and the feedback relationships between different components. This can lead to an understanding of the cellular mechanisms with opposing effects which cause paradoxical excitation. Also, the current process control techniques to avoid inverse response can be employed to avoid paradoxical excitation helping the anesthesiologist.

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Ignite Talk Session A (Wednesday) | Poster Session A (Wednesday)

Sub-threshold resonance facilitates sequential learning in biophysical neural networks.

James Roach and Michal Zochowski

Presenter: *James Roach | University of Michigan*

See Abstract 13

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Poster Session A (Wednesday)

Noisy dynamics of thermoacoustic systems prior to Hopf bifurcation

Aditya Saurabh and Lipika Kabiraj

Presenter: *Aditya Saurabh | Chair of Fluid Dynamics, Technische Universität Berlin*

This work is a report of experiments conducted in order to investigate the role of noise on thermoacoustic systems. Such systems involve nonlinear feedback coupling between combustion and acoustics. In a practical setting, such as in gas turbine combustors and furnaces, noise is inherent. In the investigation, focus is on the effect of noise prior to the Hopf bifurcation. From recent findings on general nonlinear systems, it is known that the response of a nonlinear system to noise, close to the Hopf bifurcation is defined by the phenomenon known as coherence resonance. We show that even for a thermoacoustic system, such noise-induced response arises due to the proximity of the system to the approaching Hopf bifurcation. Experiments were performed on a model thermoacoustic system undergoing a subcritical Hopf bifurcation. Coherence resonance was identified prior to the associated saddle node bifurcation such that the induced coherence depends on the noise amplitude and the proximity to the Hopf bifurcation: An optimum level of coherence is induced for an intermediate level of noise. For practical thermoacoustic systems (e.g. combustors), which are inherently noisy due to factors such as flow turbulence and combustion noise, these results can have important implications.

References:

Kabiraj et al., Phys. Rev. E., 92, 042401 (2015)

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Poster Session A (Wednesday)

Construction of Reduced Dynamics Models from High-Dimensional Time Series

Aleksei Seleznev, Dmitry Mukhin, Andrey Gavrilov and Alexander Feigin

Presenter: *Aleksei Seleznev | Institute of Applied Physics of the Russian Academy of Sciences*

Empirical modeling of a dynamical system consists in its evolution operator retrieval directly from data analysis. The most important problem in such an approach is the construction of a set of proper phase variables from time series, i.e. an embedding which captures most significant system's features underlying the observed dynamics. This task is especially important in a case of spatially-distributed data when many time series are spreaded out the system's channels. The methodology we present includes both an embedding method based on spatio-temporal data decomposition and construction of nonlinear dynamical model represented by artificial neural network. We demonstrate capabilities of the method on the example of predicting El-Nino variability from monthly sea surface temperature anomalies data within the Tropical belt.

The study is supported by Government of Russian Federation (agreement #14.Z50.31.0033 with the Institute of Applied Physics of RAS).

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Poster Session A (Wednesday)

Examining Human Unipedal Quiet Stance*Matthew Semak, Jeremiah Schwartz, Taylor McMillan and Gary Heise*Presenter: *Matthew Semak / University of Northern Colorado*

The means by which human posture control is maintained is both subtle and complex. Certainly, a great deal of past work by many researchers has afforded us valuable insights. We have a particular interest in human unipedal balance control. Data collected via a force plate for individuals attempting to maintain upright posture using their dominate and non-dominate legs. The force and jerk of the center-of-pressure for each foot has been examined using power spectral and detrended fluctuation analyses. Both the force and jerk display oscillatory behavior on long time scales. On short time scales, the jerk shows persistent correlations which can be modeled by fractional Gaussian noise, while the force is diffusive in nature. Moreover, we attempt to distinguish behavior associated with the dominate legs' dynamics from that of the non-dominate using sample entropy measurements.

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Poster Session A (Wednesday)

Quantum vortex visualization experiment*Itamar Shani, Peter Megson and Daniel Lathrop*Presenter: *Itamar Shani / University of Maryland College Park*

Quantized vortices are key features of the dynamics of quantum fields such as superfluids, Bose-Einstein condensates and superconductors. In superfluid helium a quantum vortex is a line-like topological defect around which the superfluid revolves by circular flow. Here we report an experiment in which such vortices are visualized in 3D by dispersing hydrogen particles in superfluid helium and tracking their motion. We generate a tangle of vortices by applying a uniform heat flux to a macroscopic liquid sample and observe the resulting counter-flow of viscous classical fluid and quantum superfluid. We will discuss different flow regimes and compare our experimental results to simulations and theoretical models.

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Poster Session A (Wednesday)

Entrainment of Coupled Oscillators*Jordan Snyder*Presenter: *Jordan Snyder / UC Davis*

Complex systems are ubiquitous, and often difficult to control. As a toy model for the control of a complex system, we take a system of coupled phase oscillators, all subject to the same periodic driving signal. It is well known that in the absence of coupling, this can result in each oscillator attaining the frequency of the driving signal, with a phase offset determined by the oscillator's natural frequency. We consider a special case in which the coupling tends to destabilize the phase configuration to which the driving signal would send the oscillators in the absence of coupling. In this setting we derive stability estimates that capture the trade-off between driving and coupling, and compare these results to the unforced version (i.e. the standard Kuramoto model).

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Poster Session A (Wednesday)

A developmental arc of white matter supporting a growing diversity of brain dynamics*Evelyn Tang, Chad Giusti, Graham Baum, Shi Gu, Eli Pollock, Ari Kahn, David Roalf, Tyler Moore, Kosha Ruparel, Ruben Gur, Raquel Gur, Theodore Satterthwaite and Danielle Bassett*Presenter: *Evelyn Tang / University of Pennsylvania*

As the human brain develops, it increasingly supports the coordinated synchronization and control of neural activity. The mechanism by which white matter evolves to support this coordination is not well understood. We use a network representation of diffusion imaging data to show that white matter connectivity becomes increasingly optimized for a diverse range of predicted dynamics in development. Such optimized topologies emerge across 882 youth from ages 8 to 22 evidencing increasing local specialization. Notably, stable controllers in subcortical areas are negatively related to cognitive performance. Seeking to investigate structural mechanisms that support these changes, we simulate network evolution with a set of growth rules, to find that all brain networks -- from child to adult -- are structured in a manner highly optimized for network control. We further observe differences in the predicted control mechanisms of the child and adult brains, suggesting that the white matter architecture in children has a greater potential to increasingly support brain state transitions, potentially underlying cognitive switching. This work suggests mechanisms for the propagation and stabilization of brain activity at various spatial scales, revealing a possible mechanism of human brain development that preferentially optimizes dynamic network control over static features of network architecture.

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Poster Session A (Wednesday)

Resource-transport dynamics induces criticality in networks of excitable nodes*Yogesh Virkar, Woodrow Shew, Juan Restrepo and Edward Ott*Presenter: *Yogesh Virkar / University of Colorado, Boulder*

Brain function needs to be constantly regulated to avoid too much or too little activity. More precisely, it has been hypothesized that synapse strengths are tuned so that the brain operates at the critical point of a phase transition, characterized by experimentally observed power-law distributed patterns of activity known as neuronal avalanches. A fundamental question is what mechanisms regulate the synapse strengths so that the network operates at this critical point. We propose a model where synapse strengths are regulated by metabolic resources distributed by a secondary network of glial cells. We find that this multilayer network robustly produces power-law distributed avalanches over a wide range of parameters, and that the glial cell network protects the system against the destabilizing effect of local variations in parameters. For homogeneous networks, we derive a reduced 3-dimensional map which reproduces the behavior of the full system and gives insights into the robustness of the critical state to parameter changes. We also find that the secondary glial cell network allows the neuronal network to remain at the critical point even after synapse strengths are modified when learning.

Part of this work is in Y. S. Virkar, W. L. Shew, J. G. Restrepo and E. Ott. "Feedback control stabilization of critical dynamics via resource transport on multilayer networks: How glia enable learning dynamics in the brain." *Physical Review E*, 94, 042310, 2016.

58

Poster Session A (Wednesday)

Wavenumber Selection via Spatial Parameter Step

Jasper Weinrich-Burd and Arnd Scheel

Presenter: *Jasper Weinrich-Burd | University of Minnesota*

The Swift-Hohenberg (SH) equation is a prototypical, pattern-forming model equation for Turing instability phenomena appearing in biology, laser optics, meteorology, and hydrodynamics. We study the SH equation with a space-dependent, step parameter that renders the medium stable in $x < 0$ and unstable in $x > 0$. We construct a family of steady-state solutions that represent a transition in space from a homogeneous state to a "striped" state. Solutions in the family vanish as $x \rightarrow -\infty$ and are asymptotically periodic as $x \rightarrow \infty$. Wavenumbers appearing asymptotically in the family are restricted to a neighborhood of 1 with width depending linearly on the size of the step.

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Poster Session A (Wednesday)

Dynamics of a Human Spiral Wave

Andrea Welsh, Edwin Greco and Flavio Fenton

Presenter: *Andrea Welsh | Georgia Institute of Technology*

"The Wave", also known as the "Mexican Wave", is a well-recognized group activity that takes place in stadiums and sporting events all over the world. The propagating wave has been shown to follow the dynamics of many physical, biological, and chemical systems described by reaction diffusion rules. Many of these systems have also been found to support self-sustained spiral type waves. These spiral waves, surprisingly, have been observed in the cortex of the brain, retina, intestine, uterus, tongue, skin, and heart of the human body. Spiral waves in the human heart are the underlying mechanism behind sudden cardiac death. This condition is the largest cause of natural death in the United States. We present the first demonstration of a spiral wave in a crowd of people. We have observed a "Human Spiral Wave" in a crowd of approximately 600 participants who follow a set of cellular-automata-like rules. The crowd is given an initial condition known to generate spiral waves in biological and chemical systems. By allowing the crowd to evolve in time, we have been able to observe and measure the dynamics that characterize spiral waves. These include the shape, wavelength, and period of rotation. We have observed spiral wave breakup and self-sustained turbulent dynamics. A numerical cellular-automaton model, developed using identical rules, produced spiral waves with completely different dynamics from those observed in crowds of people. This motivated us to study and estimate the effects of sensing and rule conformity in humans. We found that introducing a small amount of error and asymmetry, in the cellular-automaton model, was enough to reproduce the spiral wave dynamics observed in crowds of people. We believe that the patterns and dynamics observed in crowds of people represent a novel and entertaining system for the study of spiral waves. It is our hope, that the results presented here will garner interest in spiral waves while also raising awareness of heart arrhythmias. These experiments can easily be replicated

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Poster Session A (Wednesday)

Testing Wave Chaos Statistical Predictions in Scaled Electromagnetic Cavities

Bo Xiao, Thomas Antonsen, Edward Ott, Zachary Drikas, Jesus Gil Gil and Steven Anlage

Presenter: *Bo Xiao | University of Maryland College Park*

Predicting the induced voltage at locations inside a complex enclosure subject to an incident electromagnetic wave is a focus in many fields such as electromagnetic compatibility and telecommunication. Real life complex enclosures are usually ray-chaotic which means that the exact solution of the fields heavily depends on the geometry details and is very sensitive to small changes. Thus a statistical approach is more appropriate than trying to obtain an exact solution. The Random Coupling Model (RCM) introduced by Zheng, Antonsen and Ott is one such method to predict the statistical properties of the waves inside a ray-chaotic enclosure by using the Random Matrix Theory combined with the system-specific information represented by the radiation impedance of the ports. RCM has been widely discussed and accepted over the years with broad agreement between the theoretical predictions and experimental data, as well as simulation results. RCM is constantly expanding to include more complex scenarios, such as a cascade of coupled cavities which is the main subject of this presentation. However, to set up a cascade of cubic meter large cavities in experiment is difficult to manage and the overall size of the structure is limited by the lab space. Here we present a novel scaled cavity experimental setup in order to test the RCM prediction of the properties of waves in a chain of cavities connected through apertures and in a complicated network of cavities. The basic idea is to scale the structure down in size, so that it is manageable, and scale up the frequency and the conductivity of the walls such that the scaled structure has the same normalized loss compared to the full-size structure. Our current setup can host a scaled-down cubic volume with 450 wavelengths on each dimension, which is equivalent to the size of a house in full scale. In this talk, we present the experimental setup of the scaled cavity experiment and some result of RCM studies on a single scaled cavity, which is the first step towards more complicated networks and structures.

This work is supported by ONR under Grant No. N000141512134, AFOSR under COE Grant FA9550-15-1-0171, and the Maryland Center for Nanophysics and Advanced Materials.

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Poster Session A (Wednesday)

Characterization of BZ Reaction Phase Response Curves and Synchronization of Coupled BZ Oscillators

Desmond Yengi, Jirapa Rueangsuan, Mark Tinsley and Kenneth Showalter

Presenter: *Desmond Yengi | West Virginia University*

We report on switching synchronization patterns in a pair of coupled photosensitive BZ oscillators. Catalytic $\text{Ru}(\text{bpy})_3^{2+}$ -loaded cation exchange beads in catalyst-free BZ solutions

were perturbed with light pulses. We quantify the transient changes by constructing phase response curves from the resultant oscillations. The phase response curves measure how the phase of a BZ oscillator changes when an illumination pulse is applied. Depending on the phase at which the pulse is applied and the chemical composition of the BZ solution, the oscillations are advanced or delayed compared to the unperturbed oscillations. We present both experimental measurements and numerical simulations of the dynamical behavior of a pair of photochemically coupled BZ oscillators. An analysis of the behavior reveals phase-locked oscillations and periodic and aperiodic switching of oscillations from in-phase to out-of-phase synchronization.

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Contributed Talk (Wednesday)

Dynamics in a two-step epidemic model: Universal mechanism for hybrid percolation transitions induced by cascade dynamics

Byungnam Kahng

Presenter: *Byungnam Kahng / Seoul National University*

Hybrid percolation transitions (HPTs) induced by cascade dynamics emerge in diverse complex model systems such as k-core percolation for jamming transition, breakdown on interdependent networks in infrastructure, epidemic spreading models for disease and information. Thus far, considerable effort has been devoted to describe the properties of HPTs of individual systems. Yet the fundamental question about the possible universal mechanism underlying those HPTs has not been investigated at a microscopic level. Here, we consider a generalized epidemic model with a single initial infected node that undergoes a discontinuous transition, and find that the discontinuity results from two steps: a durable critical branching (CB) and an explosive, supercritical (SC) process. In a random network of N nodes at the transition the CB process persists for $O(N^{1/3})$ time and the remaining nodes become vulnerable. Those vulnerable nodes are activated then in the short SC process. This crossover mechanism and scaling behavior are universal for different HPT systems. On the other hand, when there are multiple initial infectious nodes, the order parameter increases continuously and shows a critical behavior with the exponent of $\beta_m = 1/2$, and at a transition point, it jumps suddenly. Moreover, the CB process persists for $O(N^{1/4})$ instead of $O(N^{1/3})$ time and other critical exponents also change.

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Invited Talk (Wednesday)

Quantifying the Predictability of Precipitation

Istvan Szunyogh and Fan Han

Presenter: *Istvan Szunyogh / University of Texas A&M*

In meteorology, precipitation is described by the scalar field of total precipitation for a specified time interval (e.g., for the past six hours). This field depends on two spatial coordinates and time. Quantifying the predictability of the spatiotemporally evolving field poses unique challenges due to the wide range of the active scales of dynamics that are involved in the evolution of the field: the spatial scales range from $\sim 0.01 \mu\text{m}$ to $\sim 1000 \text{ km}$, while the temporal scales range from split seconds to 10-15 days. The high spatiotemporal variability of the precipitation field renders the root-mean-square error inadequate to describe the growth of the amplitude of the prediction error. For instance, it indicates a complete loss of

predictability in situations where the only error in the prediction is a small relative error in the position of the precipitation system of a cyclone. Thus we propose to quantify the predictability of the precipitation field by a multi-component measure, whose components describe the predictability of the different properties of the precipitation field. The algorithmic implementation of the concept uses a morphing-based optical flow method to decide whether a predicted precipitation system can be matched or not to an observed precipitation system. If a matching system is found, the algorithm also yields a vector that describes the displacement of the predicted system. The magnitude of this vector is the displacement error. The other error components, which are the errors in the prediction of the structure and the amplitude of the predicted system, are determined after a correction of the prediction for the displacement error. We illustrate the approach by an application to operation ensemble forecasts of named winter storms of the United States, and argue that it could be used to describe the predictability of other spatiotemporally varying scalar fields with little or no modification.

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Contributed Talk (Wednesday)

A Geometrical Description of Turbulence Using Exact Coherent Structures

Balachandra Suri, Jeffrey Tithof, Ravi Kumar Pallantla, Roman Grigoriev and Michael Schatz

Presenter: *Balachandra Suri / Georgia Institute of Technology*

The dynamical systems approach to fluid turbulence relies on understanding the role of unstable, non-chaotic solutions -- such as equilibria, traveling waves, and periodic orbits -- of the Navier-Stokes equations. These solutions, called Exact Coherent Structures, exist in the same parameter regime as turbulence, but being unstable, are observed in experiments only as short transients. In this talk, we present unambiguous experimental evidence for the existence and dynamical relevance of unstable equilibria in a weakly turbulent quasi-two-dimensional (Q2D) Kolmogorov flow. In the experiment, this Q2D flow is generated in an electromagnetically driven shallow layer of electrolyte. The numerical simulations, however, use a strictly 2D model which incorporates the effects of the finite thickness of the fluid layer in the experiment. As the strength of the forcing is increased, the flow in both experiments and simulations undergoes a sequence of bifurcations, eventually becoming turbulent. In this weakly turbulent regime we find there are instances when the evolution of the flow slows down, rather dramatically, much like a pendulum slowing down in its inverted position. Using experimental flow fields from such instances, and by means of a Newton-Solver, we numerically compute several unstable equilibria. Furthermore, we provide the first experimental demonstration of an ECS based forecasting of turbulence, by showing that turbulent trajectories in the vicinity of an unstable equilibrium depart following its unstable manifold.

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Invited Talk (Thursday)

**Period Doubling Bifurcations in Cardiac Tissue;
Experiments, Theory and Simulations***Flavio Fenton*Presenter: *Flavio Fenton | Georgia Institute of Technology*

In this talk we present experimental voltage and calcium data from a variety of animal hearts (fish, rabbit, cat, dog, pig, alligator and horse) along with theory and simulations showing that several dynamical mechanisms exist in the development of the complex spatiotemporal dispersion that can initiate arrhythmias in the heart. In particular we will discuss two different types of period doubling bifurcations. If time permits we will demonstrate new methods to solve large 2 and 3D reaction diffusion systems in real time (such as 3D heart simulations) using GPUs over a web-browser, independent of machine architecture and operating system.

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Contributed Talk (Thursday)

**Computational Mechanics of Coherent Structures in
Spatiotemporal Systems***Adam Rupe, James P. Crutchfield, Karthik Kashinath and Mr Prabhat*Presenter: *Adam Rupe | University of California Davis*

The use of computer simulation and numerical solutions have become common for handling increasingly complex mathematical models of physical phenomena. This has been most successful in nonlinear systems where analytic solutions are scarce, as exemplified by the discovery of deterministic chaos. As attention moves to higher dimensional systems, gaining insight from numerical solutions is no longer trivial. Consistent identification of structures from data is currently an open problem in climate science, for instance. In particular, systems in which simple interactions propagate in a complicated manner to produce complex emergent behavior present serious difficulties for traditional mathematical analysis. Such difficulties are similar to those faced in the theory of computation. Thus a new approach to complex systems, computational mechanics, has been developed that employs the mathematical structures of computation theory to build intrinsic representations of temporal behavior, rather than relying solely on the equations of motion. A brief review of computational mechanics is given, as well as its generalization to spatiotemporal systems. Spatiotemporal computational mechanics is then used to develop a rigorous theory of coherent structures in fully discrete classical field theories with local dynamics. The method is demonstrated on the simplest such systems that support emergent structures, namely elementary cellular automata. Results are compared with a similar, but distinct, dynamical systems approach using temporally invariant sets of spatially homogeneous configurations.

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Invited Talk (Thursday)

Snakes on a plane: modeling flexible active nematics*Robin Selinger*Presenter: *Robin Selinger | Kent State University*

Active soft matter systems of self-propelled rod-shaped particles exhibit ordered phases and collective behavior that

are remarkably different from their passive analogs. In nature, many self-propelled rod-shaped particles, such as gliding bacteria and kinesin-driven microtubules, are flexible and can bend. We model these “living liquid crystals” to explore their phase behavior, dynamics, and pattern formation. We model particles as short polymers via molecular dynamics with a Langevin thermostat and various types of activity, substrate, and environments. For self-propelled polar particles gliding on a solid substrate, we map out the phase diagram as a function of particle density and flexibility. We compare simulated defect structures to those observed in colonies of gliding myxobacteria; compare spooling behavior to that observed in microtubule gliding assays; and analyze emergence of nematic and polar order. Next we explore pattern formation of self-propelled polar particles under flexible encapsulation, and on substrates with non-uniform Gaussian curvature. Lastly, we impose an activity mechanism that mimics extensile shear, study flexible particles both on solid substrates and coupled to a lipid membrane, and discuss comparisons to relevant experiments. Work performed in collaboration with Michael Varga (Kent State) and Luca Giomi (Universiteit Leiden.) Supported by NSF DMR-1409658.

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Ignite Talk Session B (Thursday)

**When Not to Grab the Bull by the Horns: Indirect Targeting
in Networks***Sean Cornelius and Adilson Motter*Presenter: *Sean Cornelius | Northeastern University*

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

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Ignite Talk Session B (Thursday)

Multivariate Dependence Beyond Shannon Information*Ryan James and James Crutchfield*Presenter: *Ryan James | UC Davis*

Accurately determining dependency structure is critical to discovering a system’s causal organization. We demonstrate that Shannon-like information measures fail at this when used to analyze multivariate dependencies. This has broad

implications, particularly when employing information to express the organization and mechanisms embedded in complex systems. Here, we do not suggest that any aspect of information theory is wrong. Rather, the vast majority of its informational measures are simply inadequate for determining the meaningful dependency structure within joint probability distributions. Therefore, such information measures are inadequate for discovering intrinsic causal relations. We close by demonstrating that such distributions exist across an arbitrary set of variables, and discuss several potential avenues toward rectifying this issue.

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Ignite Talk Session B (Thursday)
Large Deviations for Gaussian Diffusions with Delay
Robert Azencott, Brett Geiger and William Ott

Presenter: *Brett Geiger / University of Houston*

Dynamical systems driven by nonlinear delay SDEs with small noise can exhibit important rare events on long timescales. When there is no delay, classical large deviations theory quantifies rare events such as escapes from nominally stable fixed points. Near such fixed points one can approximate nonlinear delay SDEs by linear delay SDEs. Here, we develop a fully explicit large deviations framework for (necessarily Gaussian) processes X_t driven by linear delay SDEs with small diffusion coefficients. Our approach enables fast numerical computation of the action functional controlling rare events for X_t and of the most likely paths transiting from $X_0 = p$ to $X_T = q$. Via linear noise local approximations, we can then compute most likely routes of escape from metastable states for nonlinear delay SDEs. We apply our methodology to the detailed dynamics of a genetic regulatory circuit, namely the co-repressive toggle switch, which may be described by a nonlinear chemical Langevin SDE with delay.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)
Effects of Signal Inhibition on Collective Cell Migration in the Posterior Lateral Line Primordium of danio rerio
Deborah Hemingway, Rachel Lee and Wolfgang Losert

Presenter: *Deborah Hemingway / University of Maryland College Park*

Collective cell migration occurs throughout nature during phenomena such as cancer metastasis, immune response, wound healing, and morphogenesis. This study examines the in vivo collective cell migratory behaviors of the posterior lateral line primordium in embryonic danio rerio (zebrafish). We discuss the perturbations and quantified variations in the migration patterns that occur as a result of select signaling pathway inhibitions. We utilize particle image velocimetry, an analysis technique common in fluid dynamics, to analyze the biomechanical properties of directionality and migratory speed during morphogenesis.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)
Agent-based models of pattern formation on zebrafish
Alexandria Volkenev and Bjorn Sandstede

Presenter: *Alexandria Volkenev / Division of Applied Mathematics, Brown University*

Zebrafish (*Danio rerio*) is a small fish with distinctive black and yellow stripes that form on its body and fins due to the interaction of different pigment cells. Working closely with the biological data, we present an agent-based model for these stripes that accounts for the migration, differentiation, and death of three types of pigment cells on the zebrafish body. We also explore stripe formation on the caudal fin, where bone rays and fin growth seem to help direct stripes to form horizontally. The development of both wild-type and mutated patterns will be discussed.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)
Large Fluctuations and Rare-Events in Complex Networks
Jason Hindes and Ira Schwartz

Presenter: *Jason Hindes / U.S. Naval Research Lab.*

Networks form the backbone of complex systems ranging from ecological food-webs to computer and social networks, and sustain a variety of important dynamical behaviors necessary for some function or task. However, many networks of interest often operate in noisy environments and fluctuate due to random internal interactions, both of which can cause sudden transitions from one network state to another. These noise induced events can be associated with desirable outcomes, such as the extinction of an epidemic, or undesirable, such as a drastic change in network consensus. In this talk, we discuss a general theory of rare-events occurring in complex networks, including extinction and rare-opinion switches in static and adaptive topologies, that captures the transition pathway through a network between states and predicts the characteristic time-scale for switching. Lastly, using the formalism, we demonstrate how to design optimal controls that leverage fluctuations in order to enhance or inhibit rare switches in networks.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)
A network dynamics approach to identifying minimal functional subnetworks
Rasoul Rajaei, Sean Cornelius, Emma Towlson and Albert-László Barabási

Presenter: *Rasoul Rajaei / Center for Complex Network Research (BarabásiLab), Northeastern University*

How a network's microscopic dynamics translate to behavior of the system as a whole is of fundamental interest to anyone seeking to diagnose, predict, and prevent system-level failures, ranging from genetic diseases to ecosystem collapse. Yet this mapping is generally obscured by the fact that there are many microscopic configurations (e.g. the interconnections between and activities of individual species, banks, or genes) that yield the same macroscopic result (biodiversity, financial health, genetic disease). Here we study this connection between network "genotypes" and network "phenotypes" using the neuronal network of the nematode *C. elegans* equipped with

integrate-and-fire dynamics as a model system. We show that human-recognizable, organism-level behavior such as locomotion in response to touch stimuli can be accurately inferred in silico from the microscopic dynamics of the 68 body wall muscles (nodes). This capability allows us to systematically identify the ensemble of network topologies and nodal dynamics consistent with a given macroscopic function, at scales and speeds that would be unattainable through traditional in vivo experiments. We find a good correspondence between the neuronal knockouts we predict to result in a loss of functionality and those predicted by in vivo laser ablation experiments known to disrupt locomotion in the living worm. These findings lend credence to the notion that diagnosing the functionality (or lack thereof) of complex systems can be traced to the detailed features of the system's dynamics.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)

The amplification of intrinsic noise by chaos in an optoelectronic feedback loop

Kevin Fei, Joe Hart, Thomas Murphy and Rajarshi Roy

Presenter: *Kevin Fei | Harvard University*

Noise, the stochastic variation of observed quantities, is a factor fundamentally unavoidable in experimental physics. While present in all dynamical systems, its effect is especially important in chaotic dynamics. Chaos characteristically amplifies small variations in initial conditions, resulting in drastically different outcomes. It has long been claimed that chaos also amplifies intrinsic noise; that is, a chaotic system is harder to predict when the noise is fed back into the dynamics than when the noise is only present in the measurement process. To test this, we use a time-delayed optoelectronic feedback loop with a single photon detector. With our apparatus, we have the unique ability to vary the amount of intrinsic shot noise that is fed back into the system by controlling the photon rate. This allows us to experimentally demonstrate a result that has so far only been theoretically predicted and computationally verified in simple mathematical models. Our results showed quantitatively that the chaos does indeed amplify the intrinsic noise. This experiment opens the door to further investigation of the interplay between noise and chaos. The study of the impact of noise on synchronization and desynchronization of chaotic systems and entropy rates in random number generation are immediate possible applications.

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Ignite Talk Session B (Thursday)

Inhibitory Neurons Promote Robust Critical Firing Dynamics in Networks of Integrate-and-Fire Neurons

Zhixin Lu, Shane Squires, Edward Ott and Michelle Girvan

Presenter: *Zhixin Lu | University of Maryland College Park*

We study the firing dynamics of a discrete-state/discrete-time version of an integrate-and-fire neuronal network model with both excitatory and inhibitory neurons. When the integer-valued state of a neuron exceeds a threshold value, the neuron fires, sends out state-changing signals to its connected neurons. In this model, a continuous phase transition from non-ceaseless firing to ceaseless firing is observed. At criticality power-law distributions of avalanche size and duration with the previously derived exponents $-3/2$ and -2 are observed. We analytically show the condition on model parameters for

criticality by employing a mean-field method. Our main result is the demonstration that the combined presence of both inhibitory neurons and integrate-and-fire dynamics greatly enhances the robustness of critical power law behavior (i.e., there is an increased range of parameter deviation from criticality for which several decades of power law behavior occurs).

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Ignite Talk Session B (Thursday)

Leveraging Environmental Correlations: The Thermodynamics of Requisite Variety

Alexander Boyd, Jim Crutchfield and Dibyendu Mandal

Presenter: *Alexander Boyd | University of California Davis*

Key to biological success, the requisite variety that confronts an adaptive organism is the set of detectable, accessible, and controllable states in its environment. We analyze its role in the thermodynamic functioning of information ratchets---a form of autonomous Maxwellian Demon capable of exploiting fluctuations in an external information reservoir to harvest useful work from a thermal bath. This establishes a quantitative paradigm for understanding how adaptive agents leverage structured thermal environments for their own thermodynamic benefit. General ratchets behave as memoryful communication channels, interacting with their environment sequentially and storing results to an output. The bulk of thermal ratchets analyzed to date, however, assume memoryless environments that generate input signals without temporal correlations. Employing computational mechanics and a new information-processing Second Law of Thermodynamics (IPSL) we remove these restrictions, analyzing general finite-state ratchets interacting with structured environments that generate correlated input signals. On the one hand, we demonstrate that a ratchet need not have memory to exploit an uncorrelated environment. On the other, and more appropriate to biological adaptation, we show that a ratchet must have memory to most effectively leverage structure and correlation in its environment. The lesson is that to optimally harvest work a ratchet's memory must reflect the input generator's memory. Finally, we investigate achieving the IPSL bounds on the amount of work a ratchet can extract from its environment, discovering that finite-state, optimal ratchets are unable to reach these bounds. In contrast, we show that infinite-state ratchets can go well beyond these bounds by utilizing their own infinite "negentropy". We conclude with an outline of the collective thermodynamics of information-ratchet swarms.

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Invited Talk (Thursday)

An adaptive computational trade-off in turtle visual cortex

Woodrow Shew

Presenter: *Woodrow Shew | University of Arkansas*

Fundamental to the function of nervous systems is the ability to reorganize to cope with changing sensory input. Although well-studied in single neurons, how such adaptive versatility manifests in the collective population dynamics and function of cerebral cortex remains unknown. Here we measured population neural activity with microelectrode arrays in turtle visual cortex while visually stimulating the retina. First, we found that, following the onset of stimulation, adaptation tunes the collective population dynamics towards a special regime – called criticality – after an initial non-critical response.

Concurrently, we observed an adaptive tradeoff between two important aspects of visual function – sensory detection and discrimination. As adaptation tuned the cortex toward criticality, stimulus discrimination was enhanced, while stimulus detection was reduced. Our findings establish unanticipated functional benefits and costs of adaptation near criticality in visual cortex.

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Contributed Talk (Thursday)

Echo Behavior in Large Populations of Chemical Oscillators

Kenneth Showalter

Presenter: *Kenneth Showalter / West Virginia University*

Experimental and theoretical studies are reported, for the first time, on the observation and characterization of echo phenomena in oscillatory chemical reactions. Populations of uncoupled and coupled oscillators are globally perturbed. The macroscopic response to this perturbation dies out with time: At some time τ after the perturbation (where τ is long enough that the response has died out), the system is again perturbed, and the initial response to this second perturbation again dies out. Echoes can potentially appear as responses that arise at 2τ , 3τ , ..., after the first perturbation. The phase-resetting character of the chemical oscillators allows a detailed analysis, offering insights into the origin of the echo in terms of an intricate structure of phase relationships. Groups of oscillators experiencing different perturbations are analyzed with a geometric approach and in an analytical theory. The characterization of echo phenomena in populations of chemical oscillators reinforces recent theoretical studies of the behavior in populations of phase oscillators [E. Ott et al., *Chaos* 18, 037115 (2008)]. This indicates the generality of the behavior, including its likely occurrence in biological systems.

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Invited Talk (Thursday)

Scattering Theory for the Boltzmann Equation and the Arrow of Time

David Levermore

Presenter: *David Levermore / University of Maryland College Park*

We develop a scattering theory for a class of eternal solutions of the Boltzmann equation posed over all space. In three spatial dimensions, each of these solutions has thirteen conserved quantities. The Boltzmann entropy has a unique minimizer with the same thirteen conserved values. This minimizer is a local Maxwellian that is also a global solution of the Boltzmann equation – a so-called global Maxwellian. Each of the eternal solutions has a streaming asymptotic state as time goes to minus or plus infinity, but does not converge to the associated global Maxwellian as time goes to plus infinity unless it is that global Maxwellian. The Boltzmann entropy decreases as time increases, but does not decrease to its minimum as time goes to plus infinity. Said another way, the final step in the traditional argument for the heat death of the universe is not valid.

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Contributed Talk (Thursday)

Dimension from Covariance Matrices

Tom Carroll and Jeff Byers

Presenter: *Tom Carroll / Naval Research Lab*

I describe a method to estimate embedding dimension from a time series. This method includes an estimate of the probability that the dimension estimate is valid. Such validity estimates are not common in algorithms for calculating the properties of dynamical systems. The algorithm described here compares the eigenvalues of covariance matrices created from an embedded signal to the eigenvalues for a covariance matrix of a Gaussian random process with the same dimension and number of points. A statistical test gives the probability that the eigenvalues for the embedded signal did not come from the Gaussian random process.

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Invited Talk (Thursday)

Spontaneous flows in soft active matter

Zvonimir Dogic

Presenter: *Zvonimir Dogic / Brandeis University*

The laws of equilibrium statistical mechanics impose severe constraints on the properties of conventional materials assembled from inanimate building blocks. Consequently, such materials cannot exhibit autonomous motion or perform macroscopic work. Inspired by the remarkable properties of the biological cytoskeleton which is driven away from equilibrium by a conserved set of protein nanomachines, our goal is to develop soft active materials assembled from the bottom-up, using animate energy-consuming building blocks such as molecular motors and microtubule filaments. Released from the constraints of the equilibrium, these internally driven gels, liquid crystals and emulsions are able to change-shape, crawl, flow, swim, and exert forces on their boundaries to produce macroscopic work. In particular, we describe properties of an active isotropic fluid that upon confinement, transitions from a quiescent to a spontaneously flowing state. We characterize the properties of the emergent self-organized flows as well as how the transition to a flowing state depends on the properties of the confining geometry. We also describe the unique dynamics of active nematic liquid crystals, which exhibits complex streaming flows that are powered by continuous creation and annihilation of oppositely charged disclination defects. Our results illustrate how active matter can serve as a platform for testing theoretical models of non-equilibrium statistical mechanics, developing a new class of soft machines and potentially even shedding light on self-organization processes occurring in living cells.

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Contributed Talk (Thursday)

Temporal Diffraction Signatures of *C. elegans*

Jenny Mages, Harold Hastings, Adam Warner and Clara Alivisatos

Presenter: *Jenny Mages / Vassar College*

Caenorhabditis elegans is traditionally understood as a free-living beneficial soil nematode that is a powerful model organism for studying mechanisms of gene regulation, development and, more recently, for understanding sensory biology and behavior. While much is known about the neural circuitry of sensorimotor function and general locomotory patterns in *C. elegans*, to date most studies of the nematodes have been confined to two dimensions in thin films of solution

on a microscope slide. In this study we use diffraction signals that do not rely on the worm remaining in a focal plane. An organism moving in a column of fluid creates new possibilities for studying biological behaviors in a more natural environment. We are developing a real-time method to identify the environment and type of *C. elegans* using an automated signal analysis as a fingerprint. This temporal diffraction signature can be automated using standard laboratory equipment in a high-throughput setup. The diffraction signature yields a complex, possibly chaotic signal, which poses a challenging physics problem in finding the pattern in the signal and linking that to a physical system. As the physics is established we will be able to quickly identify and catalog nematodes by mutation and environment respectively. We use lag plots (time series embedding, delay embedding) also to characterize worm motion, to explore the effects of environment (lab through natural), to quantify and elucidate differences among motions of worm types, and finally to explore the complexity of these motions. There are clear differences between lag plots of the voltage signal, at delays of 160 and 320 ms for Y-200 and Y-400 respectively of moving roller type and wild type worms. The trajectory of the roller type lag plot in 2D circles a center point, suggesting a 1D attractor for roller type dynamics with weak attraction in radial attraction. The wild type trajectory is more complex, apparently due to more complex motion. In 3D, the lag plot for roller type (left) appears more planar than the lag plot for wild type, again suggesting a simpler motion. These patterns appeared consistent among most worms of the respective types. One can further describe and quantify the motion by analyzing higher dimensional embeddings, for example using attractor dimension. Finally one can quantify determinism and explore how well models, for example, simulated motion generated by the central pattern generator, fit equation-free empirical dynamics, using packages such as rEDM.

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Invited Talk (Thursday)

Ripping yourself a new one: Dynamics of Mouth Opening in Hydra

Eva-Maria Schoetz Collins

Presenter: *Eva-Maria Schoetz Collins | University of California San Diego*

Biological tissues are an exciting system to study because they are non-equilibrium materials that consist of self-propelled, interacting agents (cells) and as such exhibit interesting phenomena not observed in passive materials. In my talk I will present our recent work on Hydra mouth opening and show how functional needs drive mechanics. Hydra is a simple freshwater animal and most famous for its remarkable regenerative properties. In contrast to humans and most other animals, Hydra does not have a permanent mouth to eat. Instead, it rips a hole in its skin every time it wants to feed (check it out at: <http://shows.howstuffworks.com/now/hydra-mouth-video.htm>). Our study shows how this feat is achieved and illustrates how complex biological phenomena can be described by relatively simple physics. Our quantitative approach provides new insights into the biological mechanisms underlying these phenomena.

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Invited Talk (Friday)

Predictability of Extreme Rainfall Events via a Complex Network Approach
Juergen Kurths

Presenter: Juergen Kurths / University of Potsdam

We analyse climate dynamics from a complex network approach. This leads to an inverse problem: Is there a backbone-like structure underlying the climate system? For this we propose a method to reconstruct and analyze a complex network from data generated by a spatio-temporal dynamical system. This approach enables us to uncover relations to global circulation patterns in oceans and atmosphere. This concept is then applied to Monsoon data; in particular, we develop a general framework to predict extreme events by combining a non-linear synchronization technique with complex networks. Applying this method, we uncover a new mechanism of extreme floods in the eastern Central Andes which could be used for operational forecasts. Moreover, we analyze the Indian Summer Monsoon (ISM) and identify two regions of high importance. By estimating an underlying critical point, this leads to an improved prediction of the onset of the ISM.

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86

Contributed Talk (Friday)

Energy Harvesting from Limit Cycle Oscillations of a Flexible Structure in a Fluid Flow
Earl Dowell

Presenter: Earl Dowell / Duke University

Energy harvesting is predicated on the assumption that there are "free" sources of energy such as wind, river and ocean currents or the sun. The usual path for energy harvesting is that the "free" source creates a mechanical vibration and then using a piezoelectric material the mechanical vibration is converted to electrical energy. For this to work effectively the "free" source must have frequency content near the resonant frequencies of the mechanical device. The frequency content of the source is usually broadband and much of the source energy is not well matched to the resonant response of the mechanical system. One way to deal with this is to design (a more complicated and often nonlinear) mechanical system that responds over a broader range of frequencies. However there is a different approach that utilizes feedback between the source and mechanical system to create a Hopf bifurcation and thus a limit cycle oscillation. Both theoretical/computational and experimental results will be presented for flexible structure interacting with a fluid flow.

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Poster Session B (Friday)

Experiments in Superconducting Microwave Cavities to demonstrate Chaos Regularization of Quantum Tunneling Rates

Bisrat Addissie

Presenter: Bisrat Addissie / University of Maryland College Park

In recent past, theoretical [1] and experimental [2] work has been developed to study the statistics of the eigenstates of a domain composed of two symmetric 2D cavities separated by tunneling barrier. Of particular interest are states for which the barrier potential is higher than the state's energy, and the modes in the adjacent mirror-symmetric cavities are nearly degenerate, being only weakly coupled. In this case the small amount of coupling through the barrier causes an energy splitting between the symmetric and antisymmetric eigenstates. The variations in the splitting energies were found to be much smaller in chaotic geometries compared with their counterparts in regular geometries [1]. In our work, we find an analog in microwave cavities. Two quasi 2D aluminum cavities separated by septa formed by a series of waveguides were constructed [2]. The waveguide dimensions were selected such that the waveguides were below cut-off for the range of frequencies considered. To explore the low loss regime the cavities are cooled to temperatures below 100 mK to increase the quality factors. The scattering parameters were measured to study the statistics of the energy splitting. The results will be described in this presentation.

[1] Ming-Jer Lee, Thomas M. Antonsen, Edward Ott, and Louis M. Pecora Theory of chaos regularization of tunneling in chaotic quantum dots Phys. Rev. E 86, 056212 – Published 21 November 2012

[2] Rachel Owen, John C. Rodgers Electromagnetic Cavities as an Analog to Chaos Regularization

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Poster Session B (Friday)

Principles governing neural dynamics are scale-invariant at criticality: Renormalization approach.
Vidit Agrawal

Presenter: Vidit Agrawal / University of Arkansas

Brain research utilizes diverse measurement techniques which probe diverse spatial scales of neural activity. The majority of human brain research occurs at macroscopic scales, using techniques like functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), while microscopic electrophysiology and imaging studies in animals probe scales down to single neurons. A major challenge in brain research is to reconcile observations at these different scales of measurement. Can we identify principles of neural network dynamics that are consistent across different observational length scales? In recent experimental studies at different scales of observations, power-law distributed observables and other evidence suggest that the cerebral cortex operates in a dynamical regime near a critical point. Scale-invariance - a fundamental feature of critical phenomena - implies that dynamical properties of the system are independent of the scale of observation (with appropriate scaling). Thus, if the cortex operates at criticality, then we expect self-similar dynamical structure across a wide-range of spatial scales. Renormalization group is a mathematical tool that is used to study the scale invariance in equilibrium systems and recently, in dynamical systems with non-equilibrium critical steady-

state. In the context of neural dynamics, renormalization group ideas suggest that the dynamical rules governing the large-scale cortical dynamics may be the same as dynamics at smaller spatial scales (with appropriate coarse graining procedures). Here we investigated this possibility using a simple model of a neural network on a 2D square lattice with nearest neighbor connections. By tuning the coupling strengths, we tuned the model through a critical phase transition from a low- to a high-activity regime. We examined the model dynamics, both near and far from criticality, with different levels of coarse graining. We identified a simple coarse graining scheme that revealed scale invariant dynamical rules at criticality and quantified how dynamical rules vary with coarse graining when the model is far from criticality. Our findings held when some long-range connections were included. To our knowledge, this is the first direct application of the renormalization group framework to a neural model. Ultimately, we aim to use our coarse graining scheme on experimental data to further test the hypothesis that cerebral cortex operates near criticality.

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Poster Session B (Friday)

Complex behavior in networks of nonlinear oscillators*Leandro Alonso*

Presenter: *Leandro Alonso | Currently not affiliated, in transition. (last affiliation The Rockefeller University until June 2016)*

The purpose of this work is to explore the conditions under which smooth dynamical systems may perform computations. For this I introduce a remarkably simple network of coupled oscillators with local interactions which yields complex dynamics [1]. The model's spatio-temporal dynamics shares several features with those of cellular automata and may therefore provide insight into the dynamical mechanisms by which complexity arises in systems composed of many oscillatory units. More specifically, the model assumes that in the absence of interactions the units can present bifurcating limit cycles, and that local interactions poise the network to a critical state. The oscillators are described by a phase equation that features a SNILC bifurcation due to a non-zero first order term, and criticality is established by balancing excitation and inhibition in local patches [2]. Many biological systems can be modeled as networks of nonlinear oscillators with short-range interactions and there is growing evidence that biological networks operate near a critical regime [3,4]. The results presented here demonstrate that in networks composed of many oscillatory units with local interactions, excitability together with criticality is sufficient to give rise to complex emergent features. The model consists of a high dimensional ODE with 3 parameters and the complexity of its solutions is quantified by the permutation entropy. This measure reveals at least two broadly differentiated phases in which the network can operate, depending on the values of the parameters. The network features an absorbing phase in which most initial conditions decay to a fixed point yielding low entropy values, and a high-entropy phase in which most units are engaged in complex or chaotic spatio-temporal patterns. Complex behavior arises robustly for parameter values near the transition between these two regimes. Finally, I show that similar emergent behavior can be obtained in a simple model of neural activity that combines local bifurcations of limit cycles and critical interactions [5].

[1] Alonso LM. "Complex behavior in networks of nonlinear oscillators." (arXiv:1610.07257) (submitted, 2016)

[2] Magnasco, Marcelo O. et. al "Self-tuned critical anti-Hebbian networks." PRL (2009).

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[4] Mora, Thierry, and William Bialek. "Are biological systems poised at criticality?" Journal of Statistical Physics (2011).

[5] Alonso LM. "Emergent computation in simple model of neural activity." (in review, 2016)

90

Poster Session B (Friday)

Crash Box Response to a Drop Weight Impact Tester*Khaled Asfar, Salman Hailat and Mai Al-Qudah*

Presenter: *Khaled Asfar | JUST University*

The performance of a crash box/attenuator in a drop weight impact testing machine is investigated. Finite elements simulation is used for the transient response. The crash box/attenuator is a structure that is located in front of vehicles and used to absorb collisions and decelerate the vehicle to a complete stop. They can be placed on vehicles or on road barriers to absorb high impact in order to protect and minimize damages to frames and people. The simulation is carried out using finite element modeling where several attenuator geometries and materials such as copper, aluminum and steel were investigated. Deceleration properties and deformations were analyzed due to free drop weight testing. Three dimensional finite element models were developed for a pyramid-like crash box shape and other configurations. This program could depict the nonlinear behavior during impact. The Creo parametric ProEngineer were used to generate the geometric lattice configuration which was fed to the finite elements code. Optimized element size was used in the calculations. A scaling method was also used which lead to more accuracy and less processing time. Impact of the drop weight was simulated from falling from zero height with an initial impact velocity calculated from the desired mass initial height. Results indicated whether the attenuator fractures during or after impact if it does. Verification of the finite element solution is done through experiments.

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Poster Session B (Friday)

Phases of Space-occupying networks and relation to mammalian brain*Nima Dehmamy, Soodabeh Milanloui and Laszlo Barabasi*

Presenter: *Nima Dehmamy | Northeastern University*

Complex networks often capture abstract relations not related to physical space. But some networks, such as the brain, are physically embedded inside three dimensions and occupy space. Understanding the constraints put on networks due to being confined to 3D space may help us in tackling diseases pertaining to such spatial limitations. In the brain, these include, among others, some cases of Alzheimer's disease, Multiple Sclerosis, and possibly also Parkinson's disease. We develop a minimal model for laying out space-occupying networks, which is an extension of force-directed layouts to cases with flexible tube-like links that avoid crossing each other. We find that this model contains two phases: 1) a "universal" phase for networks in which many network topologies show similar volumetric and organizational properties; 2) a sparse phase where network topology matters. Comparing with brain statistics, we find that the universal

phase has properties similar to a class of mammalian brains. We also derive an approximate formula for the phase transition point. Relation to other classes of brains are still being investigated.

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Poster Session B (Friday)

Spectral Properties of Spiral Waves in the Barkley Model
Stephanie Dodson and Bjorn Sandstede

Presenter: *Stephanie Dodson / Brown University*

Spectral properties of spiral waves formed in the Barkley model are investigated. Absolute spectra, essential spectra, and pseudospectra of spirals are calculated using asymptotic wave trains. These results are compared with the point spectra of spirals on large disks. The spirals are computed by numerical continuation, and point spectra by iterative methods.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)

The amplification of intrinsic noise by chaos in an optoelectronic feedback loop

Kevin Fei, Joe Hart, Thomas Murphy and Rajarshi Roy

Presenter: *Kevin Fei / Harvard University*

See Abstract 75

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Poster Session B (Friday)

A Novel Model of Pulsing Oscillators
Christopher Fritz

Presenter: *Christopher Fritz / Dickinson College Dept. Physics & Astronomy*

Many oscillatory systems of great interest exhibit pulsing behavior characterized by a nonlinear phase progression such as the spiking neuron. The analysis of such oscillators has historically utilized a linear-phase model such as the Kuramoto equation to describe the system's dynamics. These models accurately describe the behavior of pulsing oscillators on larger timescales, but do not explicitly capture the pulsing nature of the system being analyzed. Indeed the Kuramoto model and its derivatives abstract from the pulsing behavior, instead using a linear phase and blurring the specific dynamics in order to fit to an analytically tractable framework. In this presentation, a novel modification is presented by introducing a phase-dependence to the frequency of each oscillator in a system of coupled oscillators. This modification induces clear pulsing behavior, and thus introduces new dynamics such as nonlinear phase progressions that more accurately reflect the nature of such systems. The analysis of this new system of equations is presented and the discovery of a heretofore unknown phenomenon termed periodic stability is described in which the phase-locked state of the system oscillates between stability and instability at a frequency determined by the mean frequency of the system. The implications of this periodic stability on the system, such as oscillations in the coherence, are discussed. The theoretical predictions made by this novel analysis are simulated numerically, and extended to real experimental systems such as electrical Wien-Bridge oscillators and neurons; systems previously described using the abstract Kuramoto model. Finally, novel dynamics of a population of these oscillators, such as wave self-organization,

are presented. The results of this work thus have clear implications on all real systems described presently by the Kuramoto model, and offer fresh insight into the analysis of such systems.

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Poster Session B (Friday)

Graph clustering of human mobility networks and its applications
Naoya Fujiwara

Presenter: *Naoya Fujiwara / Center for Spatial Information Science, The University of Tokyo*

It is one of the most important topics of the network science to understand the self-organized structures of activities of urban residents. One of the key issues is to define the geographical clusters, namely life spheres, from the data of the human mobility. It is expected that the detected clusters represent the realistic territories of activities of the residents, which are in general different from administrative districts. Moreover, the clustering results have potential applicability, such as prediction and prevention of spread of infectious diseases, and definition of effective units of policy making instead of administrative units. According to the recent development of the acquisition techniques of the big data of human mobility with such as GPS of cell phones, a novel method to determine the clusters from such big data should be developed. In the present study, we apply a graph clustering method to the network of human mobility. The network is constructed from the people flow data provided by Center for Spatial Information Science, the University of Tokyo. The data records the digitized location information based on the interview in several urban regions in Japan. The origin and destination of trips of agents in regional grids, whose size ranges from a few hundred square meter to ten square kilometer. Based on this origin-destination matrix, we consider random walks on the network in order to apply the map equation method to obtain hierarchical clusters. Our findings are summarized as follows. First, we find that the detected clusters are geographically aggregated, although we do not explicitly include information of the geographical distance between grids. Second, we observe the dependence of the cluster size on the age group of the agents; the cluster size becomes smaller for elder people. This fact reflects that the average trip distance of elder people is smaller than that of young people. This finding is important to estimate the spatial clusters of the epidemic spreading, where the behavior of elder people plays an important role. Additionally, other problems, such as the dependence of the clustering results on the grid size, are discussed in the presentation.

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Poster Session B (Friday)

Limit cycles and strange attractors of polynomial dynamical systems
Valery Gaiko

Presenter: *Valery Gaiko / United Institute of Informatics Problems, National Academy of Sciences of Belarus*

We carry out the global bifurcation analysis of polynomial dynamical systems. To control the global bifurcations of limit cycles in planar systems, it is necessary to know the properties and combine the effects of all their rotation parameters. It can be done by means of the development of new bifurcational geometric methods based on the Wintner-Perko termination

principle. Using these methods, we present, e.g., a solution of Hilbert's Sixteenth Problem on the maximum number and distribution of limit cycles for the Kukles cubic system and for the general Lienard polynomial system with an arbitrary number of singular points. Applying a similar approach, we study also three-dimensional polynomial dynamical systems and, in particular, complete the strange attractor bifurcation scenario in the classical Lorenz system connecting globally the homoclinic period-doubling, Andronov-Shilnikov, and period-halving bifurcations of its limit cycles.

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Poster Session B (Friday)

Handwritten Digit Recognition with Reservoir Computers in Software and Hardware

Aaron Griffith, Nicholas Haynes, Otti D'Huys, Daniel Canaday and Daniel Gauthier

Presenter: *Aaron Griffith | Ohio State University, Department of Physics*

In the field of machine learning, a Reservoir Computer (RC) is a model for solving classification and prediction problems using a dynamical 'reservoir' as a computational medium. Here we use RCs to perform handwritten digit recognition on the MNIST data set. To explore this application of RCs, we numerically simulate a variety of reservoirs, all constructed as networks with recurrent connections. We discover that the performance of the resulting RC only varies slightly for different choices of nonlinear function performed at each node in the network. In particular, a reservoir using Boolean values and XOR nodes still functions well at this task, despite the loss of real-valued precision. We proceed to evaluate the performance of hardware reservoirs, implemented as autonomous Boolean networks on an FPGA. We find that these hardware reservoirs perform better than equivalently-sized simulated reservoirs. A 100 node simulated reservoir can achieve a 14% error rate, while a hardware reservoir improves this to 10%.

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Poster Session B (Friday)

Chaos, noise, and physical random number generation

Joseph Hart, Yuta Terashima, Atsushi Uchida, Thomas Murphy and Rajarshi Roy

Presenter: *Joseph Hart | University of Maryland College Park*

Random number generation underlies the modern cryptographic techniques used to ensure the privacy of digital communication and storage. In order to improve security, digital information systems increasingly utilize physical entropy sources to generate high-speed unpredictable signals. Despite intense research efforts in this area, there is little consensus on how to evaluate and compare optical random number generators. Existing statistical standards, which typically consider only the final post-processed bit sequence, are ill-suited to understand and quantify the underlying physical entropy. We show that entropy rate estimates performed on the raw data not only provide a better way to quantify and compare entropy generation in different physical systems, but also can provide important information about how to best extract that entropy from the desired physical process.

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Poster Session B (Friday)

Modeling the Network Dynamics of Pulse-Coupled Neurons

David Hathcock, Kimberly Crain, Sarthak Chandra, Thomas Antonsen, Edward Ott and Michelle Girvan

Presenter: *David Hathcock | Case Western Reserve University*

We apply a mean-field approximation to investigate the macroscopic dynamics of large networks of pulse-coupled theta neurons with scale-free degree distributions and degree correlations (assortativity). Using the ansatz of Ott and Antonsen (Chaos, 19 (2008) 037113), we derive a reduced system of ordinary differential equations describing the mean-field dynamics. We find that for sufficiently large networks and degrees the solutions of the reduced system agree with those of the full network. This dimensional reduction allows for more efficient characterization of system phase transitions and attractors. We find that for networks with tightly peaked degree distributions the macroscopic behavior closely resembles that of a fully connected network. In contrast, networks with scale-free degree distributions exhibit different macroscopic dynamics due to the emergence of a degree dependent behavior. For nonassortative networks we observe transitions to a synchronously spiking state through Hopf and homoclinic bifurcations. Interestingly, the presence of either assortativity or disassortativity in the network can suppress the emergence of this synchronous state. Our results show the utility of these techniques in analyzing the effects of network topology on macroscopic behavior in neuronal networks.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)

Effects of Signal Inhibition on Collective Cell Migration in the Posterior Lateral Line Primordium of danio rerio

Deborah Hemingway, Rachel Lee and Wolfgang Losert

Presenter: *Deborah Hemingway | University of Maryland College Park*

See Abstract 71

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)

Large Fluctuations and Rare-Events in Complex Networks

Jason Hindes and Ira Schwartz

Presenter: *Jason Hindes | U.S. Naval Research Lab.*

See Abstract 73

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Poster Session B (Friday)

Effects of traumatic brain injury upon the neural dynamics and nonlinear network properties of the human brain

Andrei Irimia and John Van Horn

Presenter: *Andrei Irimia | University of Southern California*

It is widely appreciated that the complex structural, functional and morphological relationships which exist between distinct areas of the human cerebral cortex play an important role in how the brain processes information. Among the most telling of these relationships is that of structural connectivity, where distinct gyral and sulcal gray matter (GM) structures are physically connected by white matter (WM) tracts. Structural connectivity patterns allow one to understand how different networks in the brain process inputs, exchange information, and respond to either exogenous or endogenous stimuli. In addition to structural connectivity, however, various areas of the brain also share intricate relationships as a consequence of mutual trophic factors which can lead to patterns of covariation between different brain regions. Here we investigate how cortical morphometrics (cortical area, thickness, curvature), connectomics (density and length of connections between regions) and network-theoretic properties (characteristic path length, betweenness centrality, eccentricity, local efficiency, clustering and participation coefficients, nodal degree, community structure) covary across the brain and modulate the nonlinearity of information processing and exchange between distinct regions. In addition, we simulate the effects of localized lesions upon brain network topology and local information processing capabilities using anatomically accurate models of brain connectivity inferred from magnetic resonance imaging (MRI) and diffusion tensor imaging (DTI). The cortex is parcellated into gyri, sulci and extracortical regions using standard nomenclature, and network connectivity is inferred from DTI for 110 healthy adults of ages 25-36. The effect of removing gyral and sulcal structures is quantified by means of their effect upon global network architecture and processing efficiency. Through this approach, cortical lesions that result in significant vulnerability from the standpoints of network properties, information processing capabilities and consequent resilience to injury are identified, and the relationships between these findings and measurable physiological effects are discussed. This study bears significance upon the use of network theory to understand the effects of trauma, as well as upon the effort of integrating computational models of traumatic lesions with existing protocols for TBI assessment, rehabilitation and clinical care.

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Poster Session B (Friday)

Control of diffusion in random walkers*Miki Kobayashi and Hiroyasu Ando*Presenter: *Miki Kobayashi / Rissho University*

Time-delayed feedback method is known as a control method for changing chaotic motion to regular motion. We apply the feedback method to stochastic systems and demonstrate numerical simulations for a random walk and molecular dynamics. As a result, it is observed that the diffusion can be controlled by the time-delayed feedback. Specifically, the diffusion coefficient decreases drastically with increasing the delay time. Additionally, we analyze the system theoretically by using stochastic delay differential equations.

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Poster Session B (Friday)

Tunable Photonic Oscillators*Vassilios Kovanis*Presenter: *Vassilios Kovanis / Nazarbayev University*

Limit Cycle oscillators are used to model a broad range of periodic nonlinear phenomena. Using the optically injected semiconductor oscillator as a paradigm, we have demonstrated that at specific islands in the optical frequency detuning and injection level map, Period One Limit Cycle oscillation frequency is simultaneously insensitive to multiple perturbation sources. In our system these include the temperature fluctuations experienced by the master and slave lasers as well as fluctuations in the bias current applied to the slave laser. Tuning of the oscillation frequency then depends only on the injected optical field amplitude. Experimental measurements are in good quantitative agreement with numerical modeling and analysis based on a reduced Adler phase dynamics type equations. These special operating regions should prove valuable for developing ultra-stable nonlinear oscillators, such as sharp linewidth, frequency tunable photonic microwave oscillators. Finally the concept of an Isochron originally developed in mathematical biology will be reviewed and placed on context for efficient design of stable frequency sources in systems of optically coupled limit cycles oscillators [1,2].

1. Limit-Cycle Dynamics with Reduced Sensitivity to Perturbations, T.B. Simpson, Jia-Ming Liu, M. Al Mulla, NG. Usechak, and Vassilios Kovanis, Physical Review Letters, 112, 023901 (2014).

2. Tunable Oscillations in Optically Injected Semiconductor Lasers With Reduced Sensitivity to Perturbations, T.B. Simpson, Jia-Ming Liu, M. Al Mulla, NG. Usechak, and Vassilios Kovanis, Journal of Lightwave Technology 32, 3749-3758 (2014).

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Poster Session B (Friday)

Turbulent Chimera States in Large Diode Lasers Arrays*Vassilios Kovanis*Presenter: *Vassilios Kovanis / Nazarbayev University*

Large networks of semiconductor laser arrays have been investigated for fun and profit, experimentally, numerically and analytically from the viewpoint of temporal and spatial coherence for the past forty years. The Quantum Complexity and Nanotechnology Team in collaboration with the Physics Department in Astana, are currently dissecting a rather novel complex collective behavior, namely *chimera states*, where synchronized clusters of photonic emitters coexist with unsynchronized ones. For the first time, they find that such states exist in large diode arrays with nearest-neighbor interactions as the optical frequency detuning is judiciously tuned. Employing a recently proposed figure of merit by Yannis Kevrekidis for classifying chimera states, they provide quantitative and qualitative evidence for the observed dynamics. The corresponding chimeras are identified as turbulent according to the irregular temporal behavior of the classification measure. Finally they argue that such numerical explorations may be the springboard for designing next generation photonic integrated oscillators that emit at will diverse waveforms for chip scale laser radar and microwave applications.

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Poster Session B (Friday)

Development of kinks in car-following models*Douglas Kurtze*Presenter: *Douglas Kurtze / Saint Joseph's University*

Many car-following models of traffic flow admit the possibility of absolute stability, a situation in which uniform traffic flow at any density is linearly stable. Near the threshold of absolute stability, the models can be reduced to a modified Korteweg-deVries equation plus small corrections. The one-parameter family of "kink" solutions of the mKdV equation are usually of particular interest, as they represent transition zones between regions of different traffic densities. Solvability analysis shows that only one kink solution is preserved by the correction terms, and this is interpreted as a kind of selection. We point out, however, that one cannot extend the solvability analysis to a multiple-time-scales calculation, so that the solvability analysis does not point the way to any dynamical selection mechanism. Moreover, the solvability calculation requires applying an inappropriate boundary condition, so that the "selection" interpretation is not justified. We then display a two-parameter family of traveling wave solutions of the mKdV equation which describe regions of one traffic density embedded in traffic of a different density; this family includes the kink solutions as a limiting case. We carry out a multiple-time-scales calculation and find conditions under which these inclusions decay, or approach a steady state, or grow linearly.

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Poster Session B (Friday)

Statistics of chaotic resonances at optical frequencies: theory and experiments

Domenico Lippolis, Li Wang and Yun-Feng Xiao

Presenter: *Domenico Lippolis* / Jiangsu University

A deformed dielectric microcavity is used as an experimental platform for the analysis of the statistics of chaotic resonances, in the perspective of testing fractal Weyl laws at optical frequencies. In order to surmount the difficulties that arise from reading strongly overlapping spectra, we exploit the mixed nature of the phase space at hand, and only count the high-Q whispering-gallery modes directly. That enables us to draw statistical information on the more lossy, chaotic resonances, coupled to the high-Q, regular modes via dynamical tunneling.

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Poster Session B (Friday)

Nonlinear Dynamics of Directed Cell Migration

Wolfgang Losert

Presenter: *Wolfgang Losert* / University of Maryland College Park

Cells migrate as individuals or groups, to perform critical functions in life from organ development to wound healing and the immune response. While directed migration of cells is often mediated by chemical or physical gradients, our recent work has demonstrated that the physical properties of the microenvironment can also control and guide migration. I will describe how the excitable systems nature of the cytoskeleton enables cells to sense their physical environment. In particular I will review how an underlying wave-like process of the actin scaffolding drives persistent migration, and how such actin waves are nucleated and guided by the texture of the microenvironment. Based on this observation we design textures capable of guiding cells in a single preferred direction using local asymmetries in nano/microtopography on subcellular scales. This phenomenon is observed both for the pseudopod-dominated migration of Dictyostelium cells and for the lamellipod-driven migration of human neutrophils. The

conservation of this mechanism across cell types suggests that actin-wave-based guidance is important in biology and physiology.

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Poster Session B (Friday)

The Impact of Non-Orthogonal Axes on Mixing with a Bi-axial Hemispherical Piecewise Isometry

Thomas Lynn, Julio Ottino, Paul Umbanhowar and Richard Lueptow

Presenter: *Thomas Lynn* / Northwestern University

Mixing on a hemispherical shell using a bi-axial piecewise isometry (PWI) has been shown to have a broad range of mixing dynamics, but systems with non-orthogonal axes have not been studied in depth. The dynamical system obtained by iterating the PWI splits and rearranges two spherical lunes in reference to each axis, effectively cutting and shuffling the hemispherical shell. By using GPUs, the 'skeleton' of the mixing, called the exceptional set, can be investigated for a significant number of iterations of the PWI. Using the computed approximation of the exceptional set, the fractal dimension and coverage of the resulting skeleton can be measured and related to the potential for mixing independent of initial conditions. Non-orthogonal axes create a rich variety in the structure of the exceptional set and therefore mixing. Minimally mixing structures, called resonances, exist on branches that undergo pitchfork bifurcations within a smoothly varying 3-parameter space characterized by the amount of rotation about each axis and the angle between the two axes. Complex mixing regimes are also found throughout the 3-parameter space and have distinct mixing behaviors. The rate at which these mixing structures evolve and the stability of non-mixing structures to parameter variations are natural extensions of this work. Partially funded by NSF Grant #CMMI-1435065.

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Poster Session B (Friday)

Burning up: The effect of slope upon forest fire propagation

Robin M.P. Morillo and Niklas Manz

Presenter: *Niklas Manz* / The College of Wooster

We report about experimental and computational results on forest fire propagation under sloped condition. Punckt et al. [Punckt et al., Wildfires in the Lab: Simple Experiment and Models for the Exploration of Excitable Dynamics, J. Chem. Educ. 92(8), 1330-1337, 2015] used matchsticks as a lab analogue to investigate the spread of wildfires. We explore the effect of positive and negative slopes on the propagation of fire fronts i) experimentally, using various 3D printed molds with different angles to position the matches and ii) computationally, using a cellular automaton with adjusted diffusion coefficients in up and down direction. In this scaled forest we found a propagation speed dependence on the slope angle with cut-off values for negative slopes at which no waves can spread down the hill and cut-off values for positive slopes at which no clear defined fire front exists in favor of a fire burst. We will also present theoretical results about the slope effect on spiral-like fire fronts.

the attractor and analyse the corresponding dynamics. In this talk, we will show some results for some numerical and experimental datasets to validate the present method.

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Poster Session B (Friday)

Spontaneous oscillation in coupled heterogeneous excitable phase oscillators

Kai Morino, Gouhei Tanaka and Kazuyuki Aihara

Presenter: *Kai Morino / The University of Tokyo*

In this presentation, we focus on the oscillation which spontaneously emerges in coupled excitable units. Excitability is often found in biological systems. An excitable unit doesn't show oscillation without input stimulus. However, when we couple heterogeneous excitable units, oscillation spontaneously occurs. We analyze this phenomenon using two types of excitable phase units defined as $\theta(t) = 1 - \beta \sin(\theta)$ and $\theta(t) = 1 - \beta \sin(\theta + \alpha)$. The parameter α indicates the heterogeneity of the units and β indicates the degree of excitability of the units. We coupled N units which are made up of $(1 - q)N$ former units and qN latter units. In our presentation, we will report how the spontaneous oscillation varies depending on the proportion parameter q . This research was partially supported by JSPS KAKENHI Grant No. 26730127.

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Poster Session B (Friday)

Revisiting delay-embedding by using Hilbert-Schmidt integral operator theory for dynamical reconstruction

Naoto Nakano

Presenter: *Naoto Nakano / JST PRESTO / Hokkaido University*

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

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Poster Session B (Friday)

Dynamics of free scroll wave termination by low-energy electric field pulses in three dimensions

Niels Otani, Valentin Krinski, Kayleigh Wheeler and Stefan Luther

Presenter: *Niels Otani / Rochester Institute of Technology*

Recently, there has been considerable interest in developing low-energy, electric-field-based methods for defibrillating the heart. This new approach requires the study of new scenarios within which field-induced action potential waves interact with fibrillatory waves. Here, we present our latest understanding of how these induced waves, when launched from large surfaces of cardiac tissue, interact in three spatial dimensions with the scroll waves that are thought responsible for fibrillatory activity. We find that the launched waves modify the filaments around which the scroll waves rotate, causing them, in many cases, to shrink and eventually disappear, terminating the scroll wave. We have discovered, however, that this type of filament modification depends critically on the properties of the corridor through which the modified scroll wave initially rotates. The width of the corridor is typically commensurate with the width of the region initially depolarized by the electric field, which, in turn, scales like the space constant. Since the characteristic width of a rotating wave that can pass through the corridor also scales with the space constant, the success of scroll wave termination depends sensitively on numerical factors. We find that these factors depend on the electric field strength and also on the interaction of the scroll wave with the boundary. The two influences combine to allow a range of low electric field strengths that produce successful termination of the scroll wave, independent of when the electric field is applied. This is a desirable characteristic, since the phase of the scroll wave is typically not known. Thus, these observations could provide new insight in the development of a new, low-energy defibrillation method.

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Poster Session B (Friday)

Phase synchronization in active and quiet sleep in newborn infants

Nicoló Pini, Maristella Lucchini, Nina Burtchen and Maria Gabriella Signorini

Presenter: *Nicoló Pini / DEIB, Politecnico di Milano*

Cardio-respiratory coupling in human subjects refers to various bidirectional interactions between respiratory and autonomic nervous system. Growing attention has been dedicated to the phase synchronization of these systems. Our study presents an analysis of cardio-respiratory synchronization in newborns from the nonlinear dynamic viewpoint, evaluating phase locking between cardiovascular and respiratory oscillators, to highlight differences in the

interaction strength, depending on sleep states (active-quiet). This investigation is relevant given the emerging hypotheses of cardio-respiratory dysfunction as one of the causes leading to Sudden Infant Death Syndrome (SIDS). Thus, a deeper understanding of cardio-respiratory dynamics based on sleep state could expand our knowledge of related physio-pathological alterations. Moreover, there is still disagreement about which sleep state is more connected to SIDS episodes. Data from 151 newborns (Gestational Age 38-40) was analyzed: 514 three-minute epochs were considered (239 quiet 275 active). The analytic approach is based on a set of mathematical tools considering the relationship between two oscillators' instantaneous phases. In the synchronized case, phase differences should present small fluctuations around a constant, while in the unsynchronized, differences should randomly vary for every instant of time. The level of synchronization is quantified with the Synchrogram and the λ Index (>0.7), which allows reliable detection of synchronous epochs with different n:m-ratios (n heart beats during m breaths). We observed different phase-locking ratios including 3:1, 4:1, 5:1, 6:1, 3:2, 5:2. The analysis showed a significant cardio-respiratory coordination increase during quiet sleep. It is quantified as the sum of the percentage for different n:1 and n:2-ratio in a specific sleep epoch (quiet vs. active n:1-ratio: $17.59\% \pm 8.72\%$ vs. $12.16\% \pm 5.11\%$, p-value < 0.01 , quiet vs. active n:2-ratio: $10.21\% \pm 4.27\%$ vs. $4.84\% \pm 2.35\%$, p-value < 0.01). The comparison of each ratio separately shows a significant difference between quiet and active sleep for 3:1 (quiet vs. active 3:1-ratio: $5.29\% \pm 2.55\%$ vs. $3.61\% \pm 1.84\%$, p-value < 0.01). Results showed significantly higher coupling in quiet sleep, with a predominance of 3:1 phase-locking ratio. Since a physiologic purpose for cardio-respiratory coupling is still unclear, a deeper investigation is in progress. To our knowledge, it is the first time that such a characterization has been highlighted on a big dataset of newborns. As a matter of fact, cardio-respiratory coupling has been proposed as a mechanism acting to maintain rhythms within a bounded variability in weakly coupled oscillators, allowing physiological systems to respond properly to external stimuli.

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Poster Session B (Friday)

Boolean Satisfiability as Boolean Networks*Andrew Pomerance*Presenter: *Andrew Pomerance / Potomac Research LLC*

Boolean Satisfiability (SAT) is the problem of either finding an assignment to a collection of Boolean variables such that a given Boolean formula is true (i.e., the formula is satisfiable) or determining that no such assignment exists (i.e., it is unsatisfiable). It is one of the first problems to be proven NP-complete and has been extensively studied in the computer science literature for both its theoretical and practical applications. An interesting property of SAT is that there is a "hardness transition" in randomly constructed Boolean formulas: as the number of terms increases for a given number of variables, formulas go from almost surely satisfiable to almost surely unsatisfiable, and in the transition region classical algorithms perform poorly. Boolean networks are discrete-time dynamical systems that consist of a network of Boolean-valued nodes which are updated at each time step according to a function of its neighbors. An important property of these systems is whether or not they are stable in response to small perturbations. In this poster we (a) present a technique to solve SAT instances using undirected Boolean networks, (b) derive the appropriate conditions for Boolean network stability when links are bidirectional, and (c) explore

the relationship between the hardness transition in random SAT on one hand and the transition from stable to unstable dynamics in corresponding undirected Boolean networks on the other.

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Poster Session B (Friday)

Dynamical rhythms of an array of diffusively coupled BZ microoscillators with Global Negative Feedback.*Ivan Proskurkin and Vladimir K. Vanag*Presenter: *Ivan Proskurkin / Center for Nonlinear Chemistry, Baltic Federal University*

An effect of global negative feedback (GNF) on the dynamics of an array of diffusively coupled microdroplets with the oscillatory Belousov-Zhabotinsky reaction (BZ-droplets) has been studied both theoretically and experimentally. The BZ droplets produced in a microfluidic device are separated by the oil phase in a capillary and can communicate locally via inhibitor, bromine. The BZ reaction is photosensitive since the catalyst used is Ru(bpy)₃ complex. GNF is imposed through illumination of an entire capillary. The intensity of illumination is proportional to the number of the BZ-droplets in the oxidized state. Without GNF, a system of the BZ droplets possesses a large number of different oscillatory clusters, dynamics of which depends on the inhibitory coupling strength, which in turn can be regulated by the diameter of droplets. Usually, GNF generates new oscillatory clusters with larger number of droplets in clusters (and smaller number of clusters, respectively). Also GNF can create chaotic dynamics.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)

A network dynamics approach to identifying minimal functional subnetworks*Rasoul Rajaei, Sean Cornelius, Emma Towlson and Albert-László Barabási*Presenter: *Rasoul Rajaei / Center for Complex Network Research (BarabásiLab), Northeastern University*

See Abstract 74

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Poster Session B (Friday)

Optimal dynamical regularization for prediction in nonlinear inverse problems*Paul Rozdeba*Presenter: *Paul Rozdeba / University of California San Diego*

In dynamical inverse problems, the goal is to infer the values of a model system's state variables and parameters from an observed system, and then use this model system to make predictions of future observations. These observations are typically noisy, discrete in time, and the model system may contain many more state variables than there are observations.

Data assimilation solves the inverse problem by transferring information from the observed system to the model. Because of the measurement error and model uncertainty, the data assimilation is statistical. Thus, one should properly seek expected values of functions on the model's state and parameter space. These expected values are calculated using a probability distribution which is conditional on the observed data, and incorporates a prior distribution over the state variables and parameters which contains the dynamical model constraints as a regularization term. It is a well-known result in linear inverse problems that the strength of this regularization term has an optimal value for producing robust estimates and predictions, using for example the L-curve criterion with Tikhonov regularization (Hansen, 2010). The regularization strength must thus be chosen carefully in order to balance the information gained from the data and the assumptions imposed by the model. We extend this notion to nonlinear dynamical inverse problems, and using a variational approximation to a path-integral formulation of data assimilation, show that the regularization strength similarly has an optimality condition for prediction quality and robustness of state and parameter estimates. This is done primarily using an annealing algorithm developed previously (J. Ye, et al, 2015), in the case where the underlying dynamics (including stochastic elements or missing terms) of the observed system are known. This result has important implications for variational methods such as 4DVar (Talagrand and Courtier, 1987; Evensen, 2009), in which case overenforcing the model constraints may severely limit one's ability to produce high-quality predictions of an observed system.

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Poster Session B (Friday)

Propagating ring and deposition pattern of motile cells of *Escherichia coli*

Tatsunari Sakurai

Presenter: Tatsunari Sakurai | Chiba University

For living microorganisms, cells are working as smart artificial swimming devices at the microscale. For example, an individual *Escherichia coli* (*E. coli*) has an ability of motility and shows us very beautiful self-organized pattern formation in semi-solid agar [1]. To understand the pattern formation, we carried out experimentally how are the velocity of the propagating ring depended on the initial concentration of nutrient in 0.24 % semi-solid agar. There are two boundaries between a propagating ring without deposition and with deposition around 2 mM and 5 mM initial concentration of nutrient. At lower initial concentration, the velocity is increasing as increasing the initial concentration, but the relationship becomes negative at higher initial concentration. At certain initial concentration of nutrient between 2 mM and 5 mM, the deposition patterns appeared. In spite of many studies by using growth-diffusion-chemotaxis models [2, 3, 4], these models have not revealed the secrets of the pattern formation. The mechanism of the propagating ring of motile cells is also open question. We focus on how is the identity of the propagating ring maintained to understand the complex pattern formation. We would like to discuss our experimental and numerical results in this conference.

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Poster Session B (Friday)

Collective motion patterns and hybrid dynamics of swarms with networked delay coupling

Ira Schwartz, Klementyna Szwaykowska and Jason Hinds

Presenter: Ira Schwartz | US Naval Research Laboratory

The formation of coherent patterns in autonomous swarms of interacting self-propelled agents is a subject of great interest in a wide range of application areas, from engineering and physics to biology. In this work, we model and experimentally realize a mixed-reality, large-scale swarm of delay-coupled agents. Our analysis demonstrates the existence of basic stable patterns in homogeneous networks that can be achieved only with delay-coupling, and are robust to decreasing connectivity. Moreover, we find generalized forms of the basic patterns in networks with general degree distributions, and a variety of new dynamic behaviors including hybrid motions in topologies that contain a relatively small number of highly connected nodes, or "motherships." The latter is an interesting example of how heterogeneous networks can have dynamics that is a mix of different states in homogeneous networks, where high and low-degree nodes have distinct behavior simultaneously. Our results are verified through simulation as well as preliminary experimental results in a mixed-reality platform.

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Poster Session B (Friday)

Prediction of Indian Summer Monsoon Rainfall by Phase-Space Reconstruction Model

V. Krishnamurthy and A. Surjalal Sharma

Presenter: A. Surjalal Sharma | University of Maryland College Park

The prediction of the Indian summer monsoon rainfall at intraseasonal time scale is investigated in this study. The summer monsoon exhibits intraseasonal oscillations (ISOs) with different periods. The leading ISO is a nonlinear oscillation with a spectral peak centered at 45 days. This ISO has large-scale coherent spatial structure and propagates northeastward covering the Indian subcontinent, Indian and West Pacific Oceans. A prediction model, based on phase space reconstruction, is developed to predict the monsoon rainfall at subseasonal time scale. An equivalent phase space of reduced dimension can be reconstructed from a long time-series of a single or a few variables of the dynamical system. In such a phase space, the trajectory of the dynamical system can be examined to search for nearest neighbors. An ensemble of such nearest neighbors and their subsequent evolution are used to construct the prediction model. The reduced phase space is reconstructed by using a limited number of eigenmodes obtained from multi-channel singular spectrum analysis of the rainfall over the monsoon region. For this purpose, the daily gridded rainfall over India for the period 1901-2010 is used. The prediction of the monsoon rainfall by the phase space reconstruction model is shown to perform far better than the forecasts made by the US operational climate forecast model.

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Poster Session B (Friday)

Study of Phase-flip and oscillation-death in indirectly coupled oscillators*Amit Sharma, Umesh Verma and Manish Shrimali**Presenter: Manish Shrimali | Central University of Rajasthan, Ajmer, India*

We study the dynamics of indirectly coupled nonlinear oscillators. We show that indirect coupling via local dynamic environment can induce an important transitions like phase-flip and oscillation-death in identical limit cycle oscillators. This behavior is analyzed in the parameter plane by analytical and numerical studies of specific cases of the Landau-Stuart oscillator and Van der Pol oscillator. Experimental evidences of various dynamical states are shown using an electronic version of the Van der Pol oscillators. The study of phase-flip transition and oscillation quenching states will be of interest, for example in bacterial quorum sensing, where bacteria releases signaling molecules in the environment which in turn are sensed and used for population coordination. Such an environmental coupling is a more realistic and appropriate to represent delay or indirect interaction in many systems such as chemical oscillators, synthetic genetic network, neuronal system.

1. A. Sharma, and M. D. Shrimali, Phys. Rev. E 85, 057204 (2012).
2. A. Sharma, M. D. Shrimali, S. K. Dana, Chaos 22, 023147 (2012).
3. A. Sharma, U. K. Verma, and M. D. Shrimali, preprint.

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Poster Session B (Friday)

Memory Stabilization Preferentially Occurs Near a Phase-Transition*Quinton Skilling, Nicolette Ognjanovski, Sara Aton and Michal Zochowski**Presenter: Quinton Skilling | University of Michigan*

A contentious theory in computational neuroscience posits that the time activation of neurons in a neural network arrange such that they show properties of a system residing near a phase transition. The number of studies investigating this principal is vast and yet few studies have examined how residing near such a phase transition affects the storage of new memories. In this presentation, we detail an auto-associative memory model based on the Hopfield formalism in order to examine the role of critical-point dynamics in the storage of new memories. We change a control parameter over many orders of magnitude to easily tune the network dynamics to transition from order (low values) to disorder (high values) and classify whether or not dynamics are susceptible enough to novel input so that new representations can stabilize. This is accomplished by comparing how closely the final state of the network overlaps with either the natively stored configuration or one driven by novel input, not intrinsically stored in the system. Using both mean-field theory and numerical simulation, we find that the final network state marginally overlaps with the novel input-driven state only near a critical point in the phase transition. Next, we introduce a weighted, state-based learning rule which permanently changes the network structure in order to examine for which values of our control parameter, if any, novel input is stabilized in the system. We show that these changes can shift the critical point to higher values of our control parameter thus leaving the system more susceptible to stabilizing novel input. Importantly, it is only near the phase transition that new representations driven by input can stabilize. Finally, we corroborate these findings by examining the functional connectivity calculated

from in vivo neural spiking data in mice trained using the contextual fear conditioning paradigm. We quantify the stability of functional connectivity by comparing the cosine similarity calculated before and after learning. We show that functional connectivity stability reliably predicts which mice store the new fear memory by comparing to behavioral tests 24 hours after learning has occurred. Taken together, these results indicate that close proximity to a phase transition is important for the stabilization of new memories.

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Poster Session B (Friday)

Wrinkling of a thin film on a nematic liquid crystal elastomer*Harsh Soni, Robert A Pelcovits and Thomas R. Powers**Presenter: Harsh Soni | Brown University*

Wrinkles commonly develop in a thin film deposited on a soft elastomer substrate when the film is subject to compression. Motivated by recent experiments [Agrawal et al., Soft Matter 8, 7138 (2012)] that show how wrinkle morphology can be controlled by using a nematic elastomer substrate, we develop the theory of small-amplitude wrinkles of an isotropic film atop a nematic elastomer. The directors of the nematic elastomer are assumed to lie in a plane parallel to the plane of the undeformed film. For uniaxial compression of the film along the direction perpendicular to the elastomer directors, the system behaves as a compressed film on an isotropic substrate. When the uniaxial compression is along the direction of nematic order, we find that the soft elasticity characteristic of liquid crystal elastomers leads to a critical stress for wrinkling which is very small compared to the case of an isotropic substrate. We also determine the wavelength of the wrinkles at the critical stress, and show how the critical stress and wavelength depend on substrate depth and the anisotropy of the polymer chains in the nematic elastomer.

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Poster Session B (Friday)

Dynamics of a Two-Layer Tear Film with Evaporation*Michael Stapf**Presenter: Michael Stapf | University of Delaware*

Tear film thinning and hyperosmolarity can cause irritation and damage to the eye. In order to better understand these effects, we consider a model for the tear film that includes two mobile fluid layers, the aqueous and lipid layers. The lipid layer is hypothesized to act as a barrier to evaporation, leading to nonuniform thinning and the development of localized breakup, or holes, in the tear film. We examine the mechanisms that cause hyperosmolarity and holes by performing a parameter analysis for several components of this model. In vivo imaging experiments show local thinning causes increased osmolarity, as well as breakup conditions if the thinning rate is fast enough. Numerical simulations using this

model predict similar behavior, with breakup conditions after a few seconds for some parameter values.

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Poster Session B (Friday)

Four wave interaction system makes wrong predictions for the water wave problem

Danish Ali Sunny

Presenter: *Danish Ali Sunny | Institute for Analysis, Dynamics and Modelling, University of Stuttgart, Germany*

The (resonant) four wave interaction system appears as an amplitude equation in the description of gravity driven surface water waves and other dispersive wave systems. In case of non resonant quadratic terms in the original system error estimates justifying this approximation can be established with the help of normal form transformations and Gronwall's inequality. The question however, if such models, really describe the evolution of dispersive wave systems in case of resonant quadratic terms

is a difficult task. We explain that the four wave interaction system(FWI) makes wrong predictions in case of additional unstable quadratic resonances as they appear for instance for capillary-gravity surface water waves.

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Ignite Talk Session B (Thursday) | Poster Session B (Friday)

Agent-based models of pattern formation on zebrafish

Alexandria Volkening and Bjorn Sandstede

Presenter: *Alexandria Volkening | Division of Applied Mathematics, Brown University*

See Abstract 72

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Poster Session B (Friday)

Mathematical Model of Glob-Driven Tear Film Breakup (TBU)

Lan Zhong, Christiaan F. Ketelaar, Richard J. Braun, Carolyn G Begley and P. Ewen King-Smith

Presenter: *Lan Zhong | Department of Mathematical Sciences, University of Delaware*

Recently, a different type of breakup is observed, where tear film breakup (TBU) happens under or around a thick circular area of lipid in a second after blink; the thick lipid corresponds to glob. Evaporation alone will be too slow to offer a complete explanation of this breakup. Instead, a divergent flow driven by Marangoni effect was proposed to explain the rapid thinning. We examined the Marangoni-driven TBU hypothesis in a one dimensional model and an axisymmetric model by assuming the thick lipid (glob) has higher surfactant concentration, thus a lower surface tension. In both models, the thick lipid spreads out immediately due to Marangoni effect, subsequently, a strong outwards flow dragged by the corresponding shear stress leads to TBU within a second. In addition, transport of osmolarity and fluorescein are also studied in the models. TBU happens while a weak osmotic flow flows across the ocular surface. The distribution of fluorescein varied significantly with glob size. The diffusion of fluorescein is strongly affected by the competing process of flows in the tear film. The models predict that smaller globs or thinner film will decrease TBU time (TBUT). TBU will be seen under the glob, when glob is

small, otherwise TBU occurs outside the glob. This study will help provide insights about mechanism of rapid thinning and how the properties of the glob will affect TBUT and visualization of TBU.

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Poster Session B (Friday)

Nonlinear Wave Chaos and the Random Coupling Model

Min Zhou, Edward Ott, Thomas M. Antonsen and Steven M. Anlage

Presenter: *Min Zhou | University of Maryland College Park*

The Random Coupling Model (RCM) has been shown to successfully predict the statistical properties of linear wave chaotic cavities in the highly over-moded regime. The 2D -bowtie cavity characteristics have been extensively studied in the frequency range of 1-19 GHz. To introduce nonlinearity, an active nonlinear circuit is connected to two ports of the wave chaotic 1/4-bowtie cavity. The active nonlinear circuit consists of a frequency multiplier, an amplifier and several passive filters. It acts to double the input frequency in the range from 3.5 GHz to 5 GHz, and operates for microwaves going in only one direction. Measurements are taken between two additional ports of the cavity and we measure the statistics of the second harmonic voltage over an ensemble of realizations of the scattering system. We developed an RCM-based model of this system as two chaotic cavities coupled by means of a nonlinear transfer function. The harmonics received at the output are predicted to be the product of three statistical quantities that describe the three elements correspondingly. Statistical results from simulation, RCM-based modeling, and direct experimental measurements will be compared.

This work is supported by ONR under Grant No. N000141512134, AFOSR under COE Grant FA9550-15-1-0171, and the Maryland Center for Nanophysics and Advanced Materials.

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Invited Talk (Friday)

Controlling Human Microbiota

Yang-Yu Liu

Presenter: *Yang-Yu Liu | Harvard University*

We coexist with a vast number of microbes—our microbiota—that live in and on our bodies, and play an important role in human physiology and diseases. Propelled by metagenomics and next-generation DNA sequencing technologies, many scientific advances have been made through the work of large-scale, consortium-driven metagenomic projects. Despite these advances, there are still many fundamental questions regarding the dynamics and control of microbiota to be addressed. Indeed, it is well established that human-associated microbes form a very complex and dynamic ecosystem, which can be altered by drastic diet change, medical interventions, and many other factors. The alterability of our microbiome offers opportunities for practical microbiome-based therapies, e.g. fecal microbiota transplantation and probiotic administration, to restore or maintain our healthy microbiota. Yet, the complex structure and dynamics of the underlying ecosystem render the quantitative study of microbiome-based therapies extremely difficult. In this talk, I will discuss our recent theoretical progress on controlling human microbiota [1,2].

[1] Gibson TE, Bashan A, Cao H-T, Weiss ST, Liu Y-Y. On the Origins and Control of Community Types in the Human

Microbiome. PLOS Computational Biology 2016;12(2):e1004688.
 [2] Bashan A, Gibson TE, Friedman J, Carey VJ, Weiss ST, Hohmann EL, Liu Y-Y. Universality of Human Microbial Dynamics. Nature 2016;534:259-262.

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Contributed Talk (Friday)

Symmetric States Requiring System Asymmetry*Takashi Nishikawa and Adilson Motter*Presenter: *Takashi Nishikawa | Northwestern University*

Spontaneous synchronization has long served as a paradigm for behavioral uniformity that can emerge from interactions in complex systems. When the interacting entities are identical and their coupling patterns are also identical, the complete synchronization of the entire network is the state inheriting the system symmetry. As in other systems subject to symmetry breaking, such symmetric states are not always stable. Here we report on the discovery of the converse of symmetry breaking—the scenario in which complete synchronization is not stable for identically-coupled identical oscillators but becomes stable when, and only when, the oscillator parameters are judiciously tuned to nonidentical values, thereby breaking the system symmetry to preserve the state symmetry. Aside from demonstrating that diversity can facilitate and even be required for uniformity and consensus, this suggests a mechanism for convergent forms of pattern formation in which initially asymmetric patterns evolve into symmetric ones.

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Invited Talk (Friday)

Fast forward to the classical adiabatic invariant*Christopher Jarzynski*Presenter: *Christopher Jarzynski | University of Maryland College Park*

Adiabatic invariants play an important role in classical mechanics, quantum mechanics and thermodynamics. They give us the means to control the evolution of a system of interest, provided we have the patience to drive the system slowly (adiabatically). In recent years, a variety of strategies have been developed for gaining the benefits of adiabatic evolution without paying the price of slow driving. As an example, I will show how the classical action -- an adiabatic invariant -- can be preserved under non-adiabatic conditions. Specifically, for a rapidly time-dependent Hamiltonian $H(q,p,t)$ in one degree of freedom, and for an arbitrary choice of action I_0 , I will show how to construct a "fast-forward" potential energy function $V_{FF}(q,t)$ that, when added to $H(q,p,t)$, guides all trajectories with initial action I_0 to end with the same value of action. The derivation of this result is surprisingly simple, relying only on elementary manipulations of Hamilton's equations. I will also discuss how this result can be used to construct quantum shortcuts to adiabaticity, such that the quantum number is preserved (or nearly preserved) even when the Hamiltonian varies rapidly with time.

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Contributed Talk (Friday)

Flame surface patterns during thermoacoustic instability*Lipika Kabiraj, Aditya Saurabh and Christian Oliver Paschereit*Presenter: *Lipika Kabiraj | Chair of Fluid Dynamics, Technische Universität Berlin*

Thermoacoustic instability is an undesirable phenomenon, which is observed when combustion is carried out within a confinement. The cause for the occurrence of this instability is the establishment of a constructive interference between acoustic waves generated by the flame and the acoustic field of resonant modes the confinement. This phenomenon is manifested as high amplitude self-excited oscillations. The oscillations are usually damaging to the system and should hence be avoided or suppressed in practice. Flame response to the acoustic field is a key factor governing the instability. Research in the field of combustion physics and combustion technology is motivated by the need to understand how flame responds to the acoustic field--particularly its nonlinear response. Our investigation of combustion instability is based on a simple thermoacoustic setup where a premixed flat flame is stabilized on a perforated plate inside a cylindrical duct. Measurements involve acoustic pressure and flame intensity field acquisition. A critical operating parameter is varied constantly to induce a(subcritical Hopf) bifurcation to limit cycle thermoacoustic oscillations. It is observed that on changing the parameter further, the system undergoes a sequence of secondary bifurcations to chaos. At the same time, it is observed that time-varying patterns are formed on the flame during the bifurcations and simultaneously increasing amplitude of the oscillations. To investigate the response of flame to acoustic oscillations a separate experiment is carried out where the flame is acoustically forced in the absence of the confinement. The resulting flame response is nonlinear and depending on the amplitude and frequency, the external excitation also generates similar flame patterns as observed during self-excited instability. The results contain nonlinear time series analysis of the acoustic pressure and intensity oscillations and modal analysis of the high-speed imaging of the flame. Through these results we will discuss the bifurcation scenario and the simultaneous formation of the spatial-temporal, Turing-like patterns on the flame. The flame patterns in our study are not related to cellular patterns that have been reported previously for flat flames.

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Contributed Talk (Friday)

Finite-time Thin Film Rupture Driven by Modified Evaporative Loss*Hangjie Ji and Thomas Witelski*Presenter: *Hangjie Ji | Duke University, Department of Mathematics*

Rupture is a nonlinear instability resulting in a finite-time singularity as a film layer approaches zero thickness at a point. We study the dynamics of rupture in a generalized mathematical model of thin films of viscous fluids with modified evaporative effects. The governing lubrication model is a fourth-order nonlinear parabolic partial differential equation with a non-conservative loss term. Several different types of finite-time singularities are observed due to balances between conservative and non-conservative terms. Non-self-similar behavior and two classes of self-similar rupture solutions are analyzed and validated against high resolution PDE simulations.

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Contributed Talk (Friday)

Multi Chaos: A Low-Dimensional Paradigm for High Dimensional Chaos

James Yorke

Presenter: *James Yorke / University of Maryland College Park*

The most frequently studied dynamical systems are low dimensional and all the periodic orbits in a chaotic set have the same number of unstable dimensions, but this property seems to fail in high dimensional systems. In this paper, we define a property called “multi-chaos”, in which, along with the usual properties of chaos, there is a dense set of k -dimensionally unstable periodic orbits, and this holds for more than one k . We provide examples including a piecewise-linear generalized Baker map.

different software applications. Our model incorporates two distinct mechanisms: one is associated with recent decisions of users, and the other reflects the cumulative popularity of each application. Importantly, although various combinations of the two mechanisms yield long-time behavior that is consistent with data, the only models that reproduce the observed temporal dynamics are those that strongly emphasize the recent popularity of applications over their cumulative popularity. This demonstrates --- even when using purely observational data without experimental design --- that temporal data-driven modeling can effectively distinguish between competing microscopic mechanisms, allowing one to uncover previously unidentified aspects of collective online behavior.

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Contributed Talk (Friday)

Interactions of Solitary Pulses of *E. coli* in a One-Dimensional Nutrient Gradient

Glenn Young, Mahmut Demir, Hanna Salman, Bard Ermentrout and Jonathan Rubin

Presenter: *Glenn Young / Pennsylvania State University*

We study an anomalous behavior observed in interacting *E. coli* populations. When two populations of *E. coli* are placed on opposite ends of a long channel with a supply of nutrient between them, they will travel as pulses toward one another up the nutrient gradient. We present experimental evidence that, counterintuitively, the two pulses will in some cases change direction and begin moving away from each other and the nutrient back toward the end of the channel from which they originated. Simulations of the Keller-Segel chemotaxis model reproduce the experimental results. To gain better insight to the phenomenon, we introduce a heuristic approximation to the spatial profile of each population in the Keller-Segel model to derive a system of ordinary differential equations approximating the temporal dynamics of its center of mass and width. This approximate model simplifies analysis of the global dynamics of the bacterial system and allows us to efficiently explore the qualitative behavior changes across variations of parameters, and thereby provides experimentally testable hypotheses about the mechanisms behind the turnaround behavior.

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Invited Talk (Friday)

A Simple Generative Model for Collective Online Behavior

Mason Porter

Presenter: *Mason Porter / UCLA*

Human activities increasingly take place in online environments, providing novel opportunities for relating individual behaviors to population-level outcomes. We introduce a simple generative model for the collective behavior of social networking site users who are deciding between

LB1

Poster Session B (Friday) - Late-Breaking
Coarse Modeling of Circadian Rhythms in Heterogeneous Neural Networks

Tom Bertalan, C. William Gear, Yannis Kevrekidis, Michael Henson, Erik Herzog and Carlo Laing

Presenter: *Tom Bertalan / Princeton University*

The suprachiasmatic nucleus (SCN) of the hypothalamus contains about 15,000 neurons in mammals, and is the source of a light-independent 24-hour rhythm which serves as a central clock governing daily rhythms throughout the rest of the body. This rhythm is the result of a set of gene repression/promotion feedback loops occurring in each neuron. Though, in isolation, cells exhibit a range of free-running periods distributed around 24 hours, their coupling in a complex network allows for synchronization, and entrainment to an external zeitgeber. Our work on coarse-graining the dynamics of synchronized populations uses the emergent smooth dependence of cells' states in this synchronized group on the particular parameters of each cell—such as natural period. Such parameters are heterogeneous across the population, but unchanging with time. Under the assumption that this dependence is smooth (and that the cells synchronize at least partially in frequency), this coarse-graining constitutes a significant dimensionality reduction of our description of the system state. We use this reduced-dimension representation to perform optimizations of drug dosing schedules to treat non-24-hour sleep/wake disorders or to aid with entrainment to an industrial non-24-hour shift schedule.

LB2

Poster Session B (Friday) - Late-Breaking
Parameter reduction via nonlinear data-mining
Alexander Holiday, Antonios Zagaris, William Leeb, William Gear and Ioannis Kevrekidis

Presenter: *Alexander Holiday / Princeton University*

In models arising from such disparate fields as engineering and economics, investigators often find certain parameter combinations that exert almost no effect on model predictions. This problem of parameter "sloppiness" causes numerical difficulties such as slow convergence of model-fitting routines, and suggests the presence of a simpler, lower-dimensional description of the model's parameter space. While the parallel field of model reduction has seen significant research progress over the past decades, the study of parameter reduction remains relatively nascent: the Manifold Boundary Approximation Method and active subspaces are two recent, promising approaches. Here we present our own, data-based technique capable of discovering the few directions in parameter space along which model predictions vary significantly without recourse to the analytical equations that constitute the model. This provides a more general method of uncovering model sloppiness that is readily applied to a wide range of systems.

LB3

Poster Session B (Friday) - Late-Breaking
Bifurcations in a periodically stimulated limit cycle oscillator with finite relaxation times

Peter Langfield, Wilson Facanha, Bart Oldeman and Leon Glass

Presenter: *Peter Langfield / McGill University*

One of the classic problems in nonlinear dynamics involves the analysis of periodic forcing of limit cycle oscillators. Studies by Arnol'd and others show the existence of stable phase-locking in various frequency ratios between the stimulus and oscillator. The zones in frequency-amplitude parameter space with stable phase locking are called Arnol'd tongues. In addition, experimental and theoretical work shows the possibility of a range of other nonlinear phenomena including period-doubling bifurcations, multistability, and chaos. In the following, we investigate the dynamics of a model with a stable limit cycle subjected to periodic pulsatile stimuli as the amplitude and frequency of the stimulus, and the relaxation rate back to the limit cycle are varied. In this model, in the limit of infinitely fast relaxation to the limit cycle, at a critical stimulus amplitude there is a topological change of the phase resetting curve from a circle map with degree 1 to degree 0. In the two-dimensional stimulation period–stimulation amplitude parameter space, at this critical stimulus amplitude there are singular points in the bifurcation diagram where saddle-node bifurcation boundaries meet period-doubling bifurcation boundaries. For finite relaxation rates to the limit cycle, these singular points unfold to a structure in which a Neimark-Sacker bifurcation curve connects saddle-node and period-doubling bifurcation boundaries. Numerical continuation provides the essential tool to investigate these bifurcations. We expect similar features to occur in other oscillators subjected to periodic pulsatile stimuli.

LB4

Poster Session B (Friday) - Late-Breaking
Using a Large-Scale Neural Model of Cortical Object Processing to Investigate the Neural Substrate for Holding Multiple Items in Short-Term Memory and for performing a Paired Associate Task

Qin Liu, Antonio Ulloa and Barry Horwitz

Presenter: *Qin Liu / National Institutes of Health/University of Maryland College Park*

Previously, a pair of large-scale, neurobiologically realistic, multi-region computational models were constructed for simulating cortical processing of visual and auditory objects during a short-term memory task (Tagamets & Horwitz, 1998; Husain et al., 2004; Ulloa et al., 2008). The models successfully simulated cortical neuronal activities and fMRI data that generally agreed with experimental results. We have modified the structural design and connectivity of the visual model to incorporate a gating mechanism and a long-term memory component. The original visual model consisted of arrays of Wilson-Cowan-like neuronal populations representing primary and secondary visual cortices, inferior temporal cortex and PFC. We added a module representing parahippocampal cortex, which functions as a gating module, and a module representing medial temporal cortex that functions as a long-term memory store. With the gating mechanism, the model is able to hold multiple items in short-term memory and accomplish related cognitive tasks. During simulations of memorizing a list of objects, the first and the last item in the

sequence were recalled best with certain combinations of attention levels and connectivity weights, which may implicate the neural basis behind this important psychological effect (i.e., the primacy and recency effects). We also show that the model is able to perform a paired associate task with visual objects stored and associated in long-term memory. We find neuronal units that exhibit memory encoding and retrieval types of behaviors during the simulations of the paired associate task that generally match previous monkey electrophysiological experimental findings (Miyashita, 1988). Our results suggest a specific cortical architecture that reflects the neural bases by which the brain performs particular short and long term memory tasks.

LB5

Poster Session B (Friday) - Late-Breaking

Data-Mining Assisted Coarse-Grained Optimization

Dmitry Pozharskiy, Andrew Duncan, Grigorios A. Pavliotis and Ioannis G. Kevrekidis

Presenter: *Dmitry Pozharskiy | Princeton University*

The design of complex engineering systems usually leads to high-dimensional optimization problems, where the objective function is expensive to evaluate and may possess a rugged surface due to the presence of multiple local minima. In such cases gradient-based minimization methods won't be able to locate the global minima unless very specific initial conditions are chosen. We assume that some "coarse relaxation" of the objective function is smooth and we can use this underlying structure to perform coarse-grained optimization. We show that short runs of a stochastic optimization method, Simulated Annealing [1] can be described by an effective stochastic differential equation (SDE). Using appropriate subsampling we can estimate the drift and diffusion coefficients of this SDE [2] and extract information about the coarse gradient to speed up the "dynamics" of the optimization method. In addition, we show that if the data lies on a low-dimensional hyperplane in the parameter space, we can uncover it using data mining techniques such as PCA or diffusion maps [3], making the exploration of the objective function surface even more efficient.

[1] S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi, "Optimization by Simulated Annealing," *Science*, vol. 220, no. 4598, pp. 671–680, 1983.

[2] G. A. Pavliotis and A. M. Stuart, "Parameter Estimation for Multiscale Diffusions," *Journal of Statistical Physics*, vol. 127, pp. 741–781, mar 2007.

[3] R. R. Coifman, S. Lafon, A. B. Lee, M. Maggioni, B. Nadler, F. Warner, and S. W. Zucker, "Geometric diffusions as a tool for harmonic analysis and structure definition of data: diffusion maps," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 102, pp. 7426–31, may 2005.

LB6

Poster Session B (Friday) - Late-Breaking

Suppression and revival of oscillation in indirectly coupled limit cycle oscillators

Pooja Rani, Neeraj Kamal and Manish Shrivastava

Presenter: *Pooja Rani | Central University of Rajasthan, Ajmer*

We study the phenomena of suppression and revival of oscillations in a system of limit cycle oscillators coupled indirectly via a dynamic local environment. The dynamics of the environment is assumed to decay exponentially with time. We show that for appropriate coupling strength, the decay

parameter of the environment plays a crucial role in the emergent dynamics such as amplitude death (AD) and oscillation death (OD). We also show that introducing a feedback factor in the diffusion term revives the oscillations in this system. The critical curves for the regions of different emergent states as a function of coupling strength, decay parameter of the environment and feedback factor in the coupling are obtained analytically using linear stability analysis. These results are found to be consistent with the numerics and are also observed experimentally.

LB7

Poster Session B (Friday) - Late-Breaking

Ordinal Networks of Time Series

Michael Small, Konstantinos Sakellariou, Michael McCullough and Thomas Stemler

Presenter: *Michael Small | The University of Western Australia*

Over the last few years, several techniques have emerged that analyse nonlinear time series data by first constructing a network from that data. These methods seek to represent the deterministic dynamics of the underlying dynamical system as a complex network. Quantitative measures of that complex network are then used to characterise the underlying dynamics. In this contribution we review one particular family of techniques: ordinal networks. Unlike alternative techniques, ordinal networks use a form of symbolic dynamics to partition state space into regions, each of which are associated with nodes of the network. Transition between these nodes characterise transition between underlying regions of state space. The construction method which we employ has the neat side effect of characterising nodes as permutation of the integers from 1 to w , and transitions between nodes as actions on the corresponding permutation group. In addition, this particular codification is both robust to observational noise and irregular sampling, and also efficiently characterises properties of the underlying invariant density. We show, via simulations and experimental examples, the effective application of this method for characterising and classifying the dynamics of nonlinear systems undergoing bifurcation. Finally, we provide numerical and theoretical justification for connections between properties of the ordinal network and invariant measures of the original dynamical system.