XXXVII Dynamics Days Europe

June 5–9, 2017

Szeged, Hungary

Abstracts
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<td>8:45−10:00</td>
<td>Registration</td>
<td>Parallel sessions 1a 7a 10 11a</td>
<td>Parallel sessions 1b 3 14a 15</td>
<td>Parallel sessions 8b 9 13 14b</td>
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<td>10:00−11:00</td>
<td><em>Nigel Goldenfeld</em> Plenary talk</td>
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<td>11:30−12:30</td>
<td><em>Namiko Mitarai</em> Plenary talk</td>
<td><em>Simona Olmi</em> Plenary talk</td>
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<td>14:00−15:00</td>
<td><em>Odo Diekmann</em> Plenary talk</td>
<td><em>Tamas Vicsek</em> Plenary talk</td>
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**ARRIVAL**

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<td>17:20−17:45</td>
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<td>17:45−19:50</td>
<td><em>ELI attosecond: Informative Lecture</em> Welcome drink</td>
<td>Parallel sessions 4b 12b 16 17</td>
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**DEPARTURE**

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<td>Conference dinner</td>
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Conference venue:

- Albert Szent–Gyorgyi Educational Center
- Bolyai Institute
- Town Hall
MONDAY 5TH JUNE

18:00-18:40 ELI ATTOSECOND: INFORMATIVE LECTURE — Csaba Janáky
ELI-ALPS Research Institute: Research Technology and Scientific Mission

TUESDAY 6TH JUNE

9:00-9:45 REGISTRATION

9:45-10:00 OPENING
Opening by Gábor Szabó, Rector of the University of Szeged

10:00 -11:00 PLENARY 1 — Nigel Goldenfeld
Statistical Mechanics of the Phase Transition to Turbulence: Zonal Flows, Ecological Collapse and Extreme Value Statistics
Discussion leader: Valerio Lucarini

11:00-11:30 COFFEE BREAK

11:30-12:30 PLENARY 2 — Namiko Mitarai
Invasion and Extinction Dynamics in Competitive Environments
Discussion leader: Julyan Cartwright

12:30-14:00 LUNCH BREAK AND POSTER SESSION

14:00-15:00 PLENARY 3 — Odo Diekmann
Renewal Equations in Population Biology: A Dynamical Systems Perspective
Discussion leader: Ulrike Feudel

15:15-17:20 PARALLEL SESSIONS

MS2 CHEMOBRIONICS: FLUID DYNAMICS AND COMPLEXITY (Room 107)
Organizers: Silvana Cardoso, Julyan Cartwright, Gábor Schuszter
15:15-15:40 Silvana Cardoso
Self-mixing in the Earth’s Atmosphere, Oceans, and Subsurface
15:40-16:05 Julyan Cartwright
The Spark of Life: The Physics of How the Earth Went from Geology and Chemistry to Biology
16:05-16:30 Gábor Schuszter
Comparison of Flow-controlled Calcium and Barium Carbonate Precipitation Patterns for Underground Carbon Dioxide Sequestration
16:30-16:55 Oliver Steinbock
Chemobrionics Meets Microfluidics: Control of Growth Dynamics and Prebiotic Processes
16:55-17:20 Nicola Mingotti
Experimental Investigation of Turbulent Plumes with a Precipitation Reaction

MS4a COMPLEX PATTERNS ON NETWORKS (Room 211)
Organizers: Jan F. Totz, Erik Martens, Ralph G. Andrzejak
15:15-15:40 Eckehard Schöll
Chimeras in Networks with Complex Topologies
15:40-16:05 Anna Zakharova
Time-delayed Feedback Control of Noise-induced Chimera States

16:05-16:30 Ralph G. Andrzejak
Driver Response Couplings Between Networks in Chimera States

16:30-16:55 Giulia Ruzzene
Control of Chimera States Via Pacemakers

16:55-17:20 Bogdan Penkovsky
Chimera States in Nonlinear Systems with Delayed Feedback

MS8a Dynamics of Reaction Systems in Chemistry, Physical Chemistry and Biochemistry (Room 215)
Organizers: Ljiljana Kolar-Anić, Željko Ćupić

15:15-15:40 Ljiljana Kolar-Anić
Modelling of a Complex Biochemical System for Various Applications

15:40-16:05 Željko Ćupić
Influence of Circadian Function on the Dynamical States and Bifurcation Diagrams of the Hypothalamic Pituitary-adrenal Axis

16:05-16:30 Vladimir M. Marković
Modeling Hypothalamic-pituitary-adrenal Axis Dynamics under Various Forms of Externally and Internally Induced Cholesterol Perturbations

16:30-16:55 Katarina Novakovic
From Phenyl Acetylene to Mono- and Di-alkyne-terminated Poly(Ethylene Glycol) as Substrates in Oscillatory Carbonylation Reactions

16:55-17:20 Marek Orlik
Pattern Formation in the H$_2$O$_2$-based Chemical Oscillators, Caused by Inhomogeneous Temperature Field

MS12a Snapshot and Pullback Attractors, a Framework for Understanding Nonautonomous Dissipative Dynamics (Room 216)
Organizers: Michael Ghil, Tamás Tél

15:15-15:40 Michael Ghil
A Mathematical Theory of Climate Sensitivity and What We Learn About It From Pullback Attractors

15:40-16:05 Miklos Vincze
Temperature Fluctuations in a Changing Climate: an Ensemble-based Experimental Approach

16:05-16:30 Ulrike Peudel
Death and Revival of Chaos

16:30-16:55 Mátéyás Herein
The Theory of Parallel Climate Realizations as a New Framework for Teleconnection Analysis

16:55-17:20 Mickael Chekroun
Crisis of Pullback Strange Attractors in a Delay Differential Model of El Nino-Southern Oscillation
17:40-19:45 PARALLEL SESSIONS

**MS4b** COMPLEX PATTERNS ON NETWORKS (Room 211)
Organizers: Jan F. Totz, Erik Martens, Ralph G. Andrzejak

17:40-18:05 **Shashi Thutupalli**
Patterns on a Starvation Network: Aggregation and Fruiting Body Formation in Soil Bacteria

18:05-18:30 **Justus A. Kromer**
Noise-induced Patterns in Networks of Adaptive Excitable Elements

18:30-18:55 **Douglas R. Brumley**
Long-range Interactions, Wobbles, and Phase Defects in Biological Oscillator Networks

18:55-19:20 **Iryna Omelchenko**
Tweezer Control for Chimera States

19:20-19:45 **Chittaranjan Hens**
Spatio-temporal Propagation of Perturbation in Complex Networks

**MS12b** SNAPSHOT AND PULLBACK ATTRACTORS, A FRAMEWORK FOR UNDERSTANDING NONAUTONOMOUS DISSIPATIVE DYNAMICS (Room 216)
Organizers: Michael Ghil, Tamás Tél

17:40-18:05 **Valerio Lucarini**
Predicting Climate Change Using Response Theory: Global Averages and Spatial Patterns

18:05-18:30 **Tamás Bódai**
Linear Response Theory Applied to Geoengineering

18:30-18:55 **Stefano Pierini**
Pullback Attractors of a Low-order Ocean Model Subject to Periodic and Aperiodic Forcing

18:55-19:20 **György Károlyi**
Plankton-climate Interaction in Climate Change

19:20-19:45 **James A. Yorke**
Generalized Lorentz Equations

**CT16** MATHEMATICAL ASPECTS (Room 107)
Discussion leader: Tibor Krisztin

17:40-18:00 **Ilia Kashchenko**
Asymptotic of Solution of Nonlinear Equation with Two Large Delays

18:00-18:20 **Michael McCullough**
Ordinal Network Based Time Series Analysis Using Geodesic Measures

18:20-18:40 **Rene O. Medrano-T**
Cubic Homoclinic Tangency and Complex Structures of Periodicity in Planar Parameter Space

18:40-19:00 **Ulrich Parlitz**
Exploiting Delay Coordinates for Data Assimilation and Parameter Estimation
19:00-19:20 Maxim V. Shamolin  
Variety of Integrable Cases in Dynamics of Nonconservative Variable Dissipation Systems

19:20-19:40 Filippo Terragni  
Collocated POD and Simulation of Nonlinear Dynamics

19:40-20:00 Gergely Röst  
Population Dynamics of Epidemic and Endemic States of Drug-resistance Emergence in Infectious Diseases with Delayed Treatment Initiation

CT17  NETWORKS (Room 215)  
Discussion leader: István Z. Kiss

17:40-18:00 G Chiranjit Mitra  
Multi-node Basin Stability in Complex Dynamical Networks

18:00-18:20 Vladimir Klinshov  
Bistability, Rate Oscillations and Slow Rate Fluctuations in a Neural Network with Noise and Coupling Delays

18:20-18:40 František Muzika  
Symmetry Breaking in a Ring of Coupled Cells with Glycolytic Oscillatory Reaction

18:40-19:00 Viktor Novićenko  
Control of Synchronization in Complex Oscillator Networks Via Time-delayed Feedback

19:00-19:20 Márton Pósfai  
Fluctuations and Stability of Emergent Hierarchies in Social Systems

19:20-19:40 Alberto Saa  
Network Asymmetries Favor Synchronization

WEDNESDAY 7TH JUNE

8:45-10:50 PARALLEL SESSIONS

MS1a  CHEMO-HYDRODYNAMICS (Room 107)  
Organizer: Marcello A. Budroni

8:45- 9:10 Fabian Brau  
Flow Control of $A + B \rightarrow C$ Fronts by Radial Injection

9:10- 9:35 Uwe Tiele  
Sliding Drops – from Bifurcations for Single Drops to Ensemble Dynamics

9:35-10:00 Karin Schwarzenberger  
Relaxation Oscillations of Solutal Marangoni Convection at Droplets and Chains of Droplet

10:00-10:25 Reda Tiani  
Effects of Marangoni Flows on $A + B \rightarrow C$ Reaction-diffusion Fronts

10:25-10:50 Kay Huang  
Pattern Formation in Wet Granular Matter
MS7a Dynamic Network Control and Applications to Power Grids (Room 216)
Organizers: Simona Olmi, Eckehard Schöll, Anna Zakharova

8:45-9:10 Jobst Heitzig
A State Space Topology of Sustainable Management and its Implications for Power Grids

9:10-9:35 Oliver Kamps
Power Grids and Turbulence – On the Stability and Quality of Power Grids Subjected to Intermittent Feed-in

9:35-10:00 Mario Mureddu
A Statistical Approach for Resilience Analysis of ESS Deployment in Power Systems with high RES penetration

10:00-10:25 Dirk Witthaut
Network Robustness and the Impact of Transmission Line Failures

10:25-10:50 Pedro G. Lind
From Conventional to Renewable Power: Insights on the Role of Grid Heterogeneities and Long-range Connectivity

MS10 Nonlinear Delay Equations (Room 211)
Organizer: Gergely Röst

8:45-9:10 Tibor Krisztin
Smoothness Problems for Differential Equations with State-dependent Delay

9:10-9:35 Alfonos Ruiz-Herrera
Geometric Methods for Global Attraction in Systems of Delay Differential Equations

9:35-10:00 Stefan Ruschel
A Discrete Delay Epidemic Model for Isolation

10:00-10:25 Abel Garab
Morse Decomposition for Scalar Delay Difference Equations

10:25-10:50 Mónika Polner
A Space-time Finite Element Method for Neural Field Equations with Transmission Delays

MS11a Self-organization, Self-propulsion, Compartmentalization and Their Applications (Room 215)
Organizer: István L. Lagzi

8:45-9:10 Satoshi Nakata
Characteristic Motion of a Self-organized Object Based on Nonlinearity

9:10-9:35 Ádám Kun
Compartmentalization as a Prerequisite for the Origin of Life

9:35-10:00 Nobuhiko J. Suematsu
Nonlinear Behavior of a Self-propelled Droplet Coupling with the Belousov-Zhabotinsky Reaction

10:00-10:25 Taisuke Banno
Phototactic Behavior of Micrometer-sized Oil Droplets in Surfactant Solution

10:25-10:50 Veronique Pimienta
Patterns Formation in a Pulsating Drop
11:00-11:30 Coffee break

11:30-12:30 [PLENARY 4] — Simona Olmi  
The Influence of Topology and Heterogeneity in Shaping the Dynamics of Neural Networks  
Discussion leader: Edgar Knobloch

12:30-14:00 Lunch break and Poster session

14:00-15:00 [PLENARY 5] — Tamás Vicsek  
Collective Motion: from Bacteria to Drones  
Discussion leader: Kenneth Showalter

15:15-17:20 Parallel sessions

**MS5a Complicated Dynamics and Chaos in Cell Systems (Room 211)**  
Organizer: Marek Kimmel

- 15:15-15:40 Albert Goldbeter  
  Coupling the Mammalian Cell Cycle to the Circadian Clock: From Entrainment to Complex Oscillations and Chaos
- 15:40-16:05 Marek Kimmel  
  Games with Resources in Modeling of Cancer Cell Interactions
- 16:05-16:30 Franck Delaunay  
  Experimental and Theoretical Analysis of the Coupling Between the Mammalian Cell Cycle and Circadian Clock Oscillators
- 16:30-16:55 François Fages  
  Model-based Investigation of the Circadian Clock and Cell Cycle Coupling in Mouse Embryonic Fibroblasts: Prediction of RevErb-α Up-regulation During Mitosis
- 16:55-17:20 Marzena Dołbniak  
  Mathematical Modelling Reveals Unexpected Inheritance and Variability Pattern of Cell Cycle Parameters in Mammalian Cells

**MS6 Covariant Lyapunov Vectors and Applications (Room 107)**  
Organizers: Juan M. López and Valerio Lucarini

- 15:15-15:40 Valerio Lucarini  
  Statistical and Dynamical Properties of Covariant Lyapunov Vectors in a Coupled Atmosphere-ocean Model
- 15:40-16:05 Sebastian Schubert  
  Characterising Blocking-like Events in a Quasi-geostrophic Model with Covariant Lyapunov Vectors
- 16:05-16:30 Nahal Sharafi  
  Critical Transitions and Perturbation Growth Directions
- 16:30-16:55 Marcus W. Beims  
  Alignment of Lyapunov Vectors: A Quantitative Criterion to Predict Large Events?
- 16:55-17:20 Juan M. López  
  Fluctuations of Lyapunov Exponents in Extended Chaotic Systems
MS7b DYNAMICAL NETWORK CONTROL AND APPLICATIONS TO POWER GRIDS (Room 216)  
Organizers: Simona Olmi, Eckehard Schöll, Anna Zakharova  
15:15-15:40 Giovanni Filatrella  
Josephson Junctions as a Prototype for Synchronization of Nonlinear Oscillators:  
from Huygens Clocks to the Utility Power Grid  
15:40-16:05 Benjamin Schäfer  
Dynamics of Decentrally Controlled Power Grids  
16:05-16:30 Rosaria Volpe  
A Mathematical Model for Energy Distribution in Urban Areas  
16:30-16:55 Jan Philipp Pade  
Towards the Impact of Structural Perturbations in Power-grid: the Role of Algebraic  
Constraints  
16:55-17:20 Yuri Maistrenko  
Solitary States in the Kuramoto Model with Inertia

MS11b SELF-ORGANIZATION, SELF-PROPULSION, COMPARTMENTALIZATION AND THEIR  
APPLICATIONS (Room 215)  
Organizer: István L. Lagzi  
15:15-15:40 Federico Rossi  
Giant Vesicles as Host Reactors for Nonlinear Chemical Reactions  
15:40-16:05 Annette Taylor  
Directing the Motion of Aspirin Tablets on Curved Air-water Interfaces  
16:05-16:30 Takashi Isoshima  
Wavefront Propagation in Two-dimensional Optical Bistable Device for Maze  
Exploration  
16:30-16:55 István L. Lagzi  
Maze Solving Using Self-propelled and Passive Particles at the Liquid-air Interface  
16:55-17:20 Jitka Čejková  
Artificial Chemotaxis of Decanol Droplet Groups

17:20-17:40 COFFEE BREAK

17:40-19:20 PARALLEL SESSIONS

MS5b COMPLICATED DYNAMICS AND CHAOS IN CELL SYSTEMS (Room 211)  
Organizer: Marek Kimmel  
17:40-18:05 Milan Stehlik  
Extracting Fractal and Extreme Aspects from Series of Random Dynamical Systems  
18:05-18:30 Monika Kurpas  
Thick Distribution Tails and Super-exponential Growth in Models of Cancer  
Secondary Tumors

CT18 APPLICATIONS (Room 215)  
Discussion leader: Marcus J. B. Hauser  
17:40-18:00 Bulesú Sándor  
The Role of Attractors in the Closed-loop Scheme of Robotic Locomotion  
18:00-18:20 Ferenc Hegedűs  
Topological Description of Periodic Structures of an Asymmetric Nonlinear Oscillator
18:20-18:40 **Masanobu Inubushi**
Reservoir Computing Beyond Memory-Nonlinearity Trade-off

18:40-19:00 **Jürgen Vollmer**
Characterizing Rare Fluctuations in Soft Particulate Flows

19:00-19:20 **Hiromichi Suetani**
Lyapunov Analysis of Chaotic Itinerancy in FORCE-based Neural Network Learning

**CT19 CHAOTIC SYSTEMS (Room 216)**
*Discussion leader: Vilmos Gáspár*

17:40-18:00 **Itzhack Dana**
Quantum Dynamical and Topological Manifestations of Superweak Chaos

18:00-18:20 **Ezequiel del Rio**
Noise Effect on the New Theory of Intermittency

18:20-18:40 **Hildegard Meyer-Ortmanns**
Physical Aging and Emerging Long-period Orbits in Deterministic Classical Oscillators

18:40-19:00 **Jordi Tiana-Alsina**
Optimal Entrainment of the Spikes Emitted by a Semiconductor Laser with Feedback

19:00-19:20 **Fumiyoshi Kuwashima**
High Efficient THz Wave Detections Using Metal V-grooved Waveguide(MVG) and Generations Using Laser Chaos

**CT20 ENVIRONMENTAL SYSTEMS (Room 107)**
*Discussion leader: Annette Taylor*

17:40-18:00 **Tímea Haszpra**
The Effect of Climate Change on the Topological Entropy of Atmospheric Pollutant Clouds

18:00-18:20 **Evgeniy Khain**
Noise-induced Rare Events in Granular Media: a Volcanic-like Explosion

18:20-18:40 **Tamás Kovács**
Recurrence Time Analysis in Exoplanetary Dynamics

18:40-19:00 **Constantinos I. Siettos**
A Biophysical Network Model for Antisaccade Eye Movements

19:00-19:20 **Cristina G. B. Martínez**
The Interplay of Synchronization in Epilepsy and Sleep: A Data-driven Approach

19:30-20:30 **ROUND TABLE DISCUSSION**
Ulrike Feudel, Michael Ghil, Albert Goldbeter, Marek Kimmel, Kenneth Showalter, James A. Yorke
*What is the Future of Dynamics?*
*Discussion leader: Eckehard Schöll*
THURSDAY 8TH JUNE

8:45-10:50 PARALLEL SESSIONS

**MS1b CHEMO-HYDRODYNAMICS** (Room 107)
*Organizer: Marcello A. Budroni*

8:45- 9:10 **Pier Luigi Gentili**
Hydrodynamic Photochemical Oscillators Useful for Chaos Computing

9:10-9:35 **Izabella Benczik**
Transient Chaos in Chemically Leaked Open Flows

9:35-10:00 **Dario M. Escala**
Hydrodynamic Instabilities Driven by Complex Chemical Reactions

10:00-10:25 **Marcus J. B. Hauser**
Laminar Mixing in Tubular Networks of Plasmodial Slime Moulds

10:25-10:50 **Yves Méheust**
The Interplay Between Solute Mixing and Chemical Reaction in 2D Porous Media

**MS3 COMPLEX NETWORKS: DELAYS AND COLLECTIVE DYNAMICS** (Room 215)
*Organizers: Yuliya Kyrychko and Konstantin Blyuss*

8:45- 9:10 **Eckehard Schöll**
Control of Chimeras by Time Delay in Dynamical Networks

9:10- 9:35 **Jan Sieber**
Local Bifurcations in Delay Equations with State-dependent Delays

9:35-10:00 **Arindam Saha**
Generation and Propagation of Delay-induced Extreme Events in Spatially Extended Systems

10:00-10:25 **Oleh Omel’chenko**
Bifurcations Mediating Appearance of Chimera States

10:25-10:50 **Konstantin Blyuss**
Time-delayed Model of RNA Interference

**MS14a SYNCHRONIZATION PATTERNS IN NETWORKS: THEORY AND APPLICATIONS** (Room 216)
*Organizers: István Z. Kiss and Oleh Omel’chenko*

8:45- 9:10 **Ralf Toenjes**
The Effects of Noise on an Oscillator Ensemble Coupled in a Star-graph Configuration

9:10- 9:35 **Hiroshi Kori**
Optimal Network Motif for Synchronization in Coupled Noisy Oscillators

9:35-10:00 **Kenneth Showalter**
Echo Behavior in Large Populations of Chemical Oscillators

10:00-10:25 **Oleksandr V. Popovych**
Pulsatile Delayed Feedback for Closed-loop Deep Brain Stimulation

10:25-10:50 **Inmaculada Leyva**
Inter-layer Relay Synchronization in Multiplex Networks
**MS15 THz Wave and Laser Dynamics (Room 211)**

*Organizers: Fumiyoshi Kuwashima and Takashi Isoshima*

8:45-9:10 Hiroaki Minamide
Efficient Terahertz-wave Generation and Detection Based on Dynamic Nonlinear Effect

9:10-9:35 Masahiko Tani
Terahertz Time-domain Coherent Raman Spectroscopy Using Picosecond Frequency-chirped Optical Pulses

9:35-10:00 Alexandre Locquet
Time-resolved Terahertz Spectroscopy and Laser Dynamics

10:00-10:25 Satoshi Sunada
Mode Competition Dynamics in Micro Cavity Lasers

10:25-10:50 Satoshi Ebisawa
Chaotic Oscillation of Laser Diode with Optical Injection and Pseudorandom Signal

11:00-11:30 Coffee Break

11:30-12:30 Plenary 6 — Antonio Politi
Quantifying the Dynamical Complexity of a Time-series from Ordinal Patterns
*Discussion leader: James A. Yorke*

12:30-14:00 Lunch Break and Poster Session

14:00-15:00 Plenary 7 — Oliver Steinbock
Vortex Dynamics: A Journey Through Chemistry and Cardiology
*Discussion leader: Patrick De Kepper*

15:00-19:00 Sightseeing – Excursion

19:30-21:30 Conference Dinner

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**FRIDAY 9TH JUNE**

8:45-10:50 Parallel Sessions

**MS8b Dynamics of Reaction Systems in Chemistry, Physical Chemistry and Biochemistry (Room 215)**

*Organizers: Ljiljana Kolar-Anić, Željko Ćupić*

8:45-9:10 Stevan Mačesić
Method for Determination of Mechanisms Responsible for Complex Dynamics in the Model of Bray-Liebhafsky Reaction

9:10-9:35 Kristina Stevanović
The Application of Stopped-flow Technique for Investigation of Reaction Dynamics of Iodine Oxidation with Hydrogen Peroxide

9:35-10:00 Attila K. Horváth
Robust and Detailed Kinetic Model of the Chlorite-thiosulfate Reaction

10:00-10:25 Cédric Barroo
Emergence of Chemical Oscillations from Nanosized Target Patterns
10:25-10:50 \textbf{Teresa Kowalska}  
Assessment of Dynamics of the Oscillating Reactions with Chiral Compounds

\textbf{MS9} \textbf{Fluid Dynamics Simulation Tools Through the Eye of the Physicist}  
(Room 107)  
\textit{Organizer: Izabella Benczik}  
8:45-9:10 \textbf{Mátyás Herein}  
A User Friendly Climate Model: The Planet Simulator  
9:10-9:35 \textbf{Gábor Drótos}  
The Dynamics and Its Parameter Dependence of Radiative–Convective Equilibrium in ECHAM6.3  
9:35-10:00 \textbf{Markus Knodel}  
Dynamics of Hepatitis C Virus Replication in Single Liver Cells: Full 3D (surface) PDE Modeling with UG4

\textbf{MS13} \textbf{Stability in Non-autonomous Complex Dynamics}  
(Room 211)  
\textit{Organizer: Aneta Stefanovska}  
8:45-9:10 \textbf{Spase Petkoski}  
Time-varying Kuramoto Model  
9:10-9:35 \textbf{Maxime Lucas}  
Nonautonomous Perturbation Stabilises Dynamics of Complex System  
9:35-10:00 \textbf{Michael Ghil}  
Non-autonomous Delay-differential Models of the El Niño–Southern Oscillation and Their Pullback Attractors  
10:00-10:25 \textbf{Paul Ritchie}  
Early-warning Indicators for Rate-induced Tipping  
10:25-10:50 \textbf{Gemma Lancaster}  
Dynamics of Cellular Energy Metabolism

\textbf{MS14b} \textbf{Synchronization Patterns in Networks: Theory and Applications}  
(Room 216)  
\textit{Organizers: István Z. Kiss and Oleh Omel’chenko}  
8:45-9:10 \textbf{Oleh Omel’chenko}  
Noninvasive Model Reconstruction from a Partially Synchronized State  
9:10-9:35 \textbf{Edgar Knobloch}  
Chimera States in Nonlocally Coupled Oscillators  
9:35-10:00 \textbf{Jan F. Totz}  
Experimental Observation of Spiral Wave Chimeras in Coupled Chemical Oscillators  
10:00-10:25 \textbf{Viktor Horváth}  
Pulse-coupled Chemical Oscillators: Experiments, Models, Theory
10:25-10:50 István Z. Kiss
Partially Synchronized States in Small Networks of Electrochemical Oscillators:
Effect of Heterogeneities and Network Topology

11:00-11:30 Coffee Break

11:30-12:30 [Plenary 8] — Tomaz Prosen
Quantum Chaos in Clean Many-Body Systems
Discussion leader: Eckehard Schöll

Wind Energy with Regard to Nonlinear and Stochastic Dynamics
Discussion leader: Tamás Tél

13:30-13:40 Closing
Plenary talks
Plenary 1

TUESDAY 10:00 – 11:00

Statistical Mechanics of the Phase Transition to Turbulence: Zonal Flows, Ecological Collapse and Extreme Value Statistics

Hong-Yan Shih, Tsung-Lin Hsieh, and Nigel Goldenfeld

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How do fluids become turbulent as their flow velocity is increased? In recent years, careful experiments in pipes and Taylor-Couette systems have revealed that the lifetime of transient turbulent regions in a fluid appears to diverge with flow velocity just before the onset of turbulence, faster than any power law or exponential function [1]. I show how this superexponential scaling of the turbulent lifetime in pipe flow is related to extreme value statistics [2], which I show is a manifestation of a mapping between transitional turbulence and the statistical mechanics model of directed percolation [3]. This mapping itself arises from a further surprising and remarkable connection: laminar and turbulent regions in a fluid behave as a predator-prey ecosystem [4]. Such ecosystems are governed by individual fluctuations in the population and being naturally quantized, are solvable by path integral techniques from field theory. I explain the evidence for this mapping, and propose how a unified picture of the transition to turbulence emerges in systems ranging from turbulent convection to magnetohydrodynamics.

Acknowledgment

We thank A. Willis for permission to use his code ‘Open Pipe Flow’ 23. This work was partially supported by the National Science Foundation through grant NSF-DMR-1044901.

References

Plenary 2

Invasion and Extinction Dynamics in Competitive Environments

Namiko Mitarai

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Ecological systems comprise an astonishing diversity of species. The interactions are often competitive, and sometimes introduction of a new species does not increase biodiversity but causes a cascade of extinctions. Yet, the high diversity of species can be maintained in the long term. In the talk, we introduce some of the models that may shed lights on the invasion and extinction dynamics of species that eventually leads to high diversity of species.

We first focus on the constraints on the interaction network structure and resulting dynamics in a simple ecosystem model. The examples include the interaction between phage and bacteria, that can be described by a generalized Lotka-Volterra equations when the system is well-mixed [1]. Such a description can be extended to a foodweb that has multiple trophic levels [2, 3]. We have shown that coexistence in a foodweb with strict trophic levels is constrained by the food web assembly rules, where each species can be seen as contributing to a non-overlapping consumer resource pair, either as a free consumer or a controlled resource. These assembly rules are ultimately based in a generalization of the competitive exclusion principle to Lotka-Volterra food webs with an arbitrary number of species [2].

Based on this rule, we provide a minimal theory of the evolution of a food web by invasion of new species. The theory is minimal, as we assume that each species only feeds on a single resource, leading to a hierarchical, tree-like food web. We prove that at each invasion step there is one uniquely determined outcome: either the invader peacefully coexists with the residents and resources are re-distributed; the invader is eliminated; or one or several of the resident species are removed in a uniquely defined extinction cascade. At the end of either of these processes the resulting food web relaxes to a globally stable (and feasible) steady state. We break down the essence of our theory in the conceptual invasion extinction model (IEM), which allows us to analytically compute the persistence time and the extinction size distribution.

We then turn our focus on another important factor for the coexistence, the effect of the spatial structure. Even in a simple system as phage-bacteria interaction, inhomogeneity in space provides an nontrivial patterns in the death and growth of bacteria [4]. We introduce a toy model of sessile species with competitive random interaction network. We assume that a new species invades the system at a very low rate, that can cause extinction of existing species but also the increase of diversity in the system. When we restrict the interaction with nearest neighbor sites on a two dimensional lattice, the model shows a discontinuous transition from a low-diversity state to a high-diversity state when the interaction density in the assigned interaction network falls below 5\sim10\%[5, 6]. We show that patches of isolated meta-populations created by cyclic interactions among the species is a key for the high-diversity state [7].

References


Plenary 3

Renewal Equations in Population Biology: a Dynamical Systems Perspective

Odo Diekmann

Mathematical Institute, Utrecht University, Netherlands

A delay equation is a rule for extending a function of time towards the future on the basis of the (assumed to be) known past. In case of delay differential equations, the rule specifies the derivative in the point of extension and the default state space consists of continuous functions. In case of renewal equations, the rule specifies the function value itself and the default state space consists of integrable functions. In both cases one defines a dynamical system by translation along the extended function, see [1].

Renewal equations should be omnipresent in Population Dynamics and Infectious Disease Epidemiology, see [2], but many modelers strive to avoid them, presumably for two reasons: unfamiliarity and lack of user friendly numerical tools. A recent attempt to amend the situation concerning numerical bifurcation methods is reported in [3,4]. The aim of the talk is to review both the motivating applications and the state-of-the-art of the theory.

References

The Influence of Topology and Heterogeneity in Shaping the Dynamics of Neural Networks

Simona Olmi

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In this talk I will discuss the role played by the topology and heterogeneity in promoting coherent activity in pulse-coupled neural networks at a microscopic and macroscopic level. Firstly, an excitatory diluted random network will be considered, where neurons are connected as in a directed Erdös-Renyi graph with average connectivity scaling (sub-)linearly with the number of neurons in the network. In these “massively connected” networks it has been shown that in the thermodynamic limit the dynamics of coherent collective states coincide with that of fully coupled networks [1, 2]. In particular, the random dilution of the connections induces inhomogeneities in the neuronal behaviors for any finite system size, promoting a weak form of chaos, which vanishes in the thermodynamic limit. In this limit, the disordered systems exhibit regular (non chaotic) dynamics thus recovering the properties of a homogeneous fully connected network. The situation is quite different for a "sparse network" characterized by a constant in-degree. In this case, on one side it has been found that a few tens of random connections are sufficient to sustain a nontrivial collective dynamics, furthermore the collective motion coexists with a microscopically chaotic dynamics that does not vanish in the thermodynamic limit and turns out to be extensive [3]. Extensive chaos has been already found in spatially extended system with nearest-neighbor coupling (diffusive coupling) induced by the additivity of the system. In the present case this property is highly nontrivial, as the network dynamics is non additive and it cannot be approximated as the juxtaposition of almost independent sub-structures. In the second part of the talk I will consider inhibitory networks. In particular, I will present a general effect emerging in heterogeneous inhibitory networks: inhibition can induce not only suppression of the neural activity, as expected, but when sufficiently strong it can promote neural reactivation. In particular, in globally coupled networks the fraction of neurons actively participating to the neural dynamics decreases monotonically with the synaptic strength. A different scenario emerges for sparse networks, here for small inhibition one observes an asynchronous tonic activity of nearly independent supra-threshold neurons, while at large synaptic strengths a transition occurs towards a regime where the neurons are all effectively sub-threshold, while their irregular firing is due to current fluctuations. In this context, a neuron can be silent (dead) due to the inhibitory action of its presynaptic neighbors, and its firing (rebirth) can be interpreted as the passage of a threshold due to an activation process induced by current fluctuations. This transition from mean-driven to fluctuation-driven dynamics is observable for instantaneous and non-instantaneous synapses. For sufficiently slow synapses the transition becomes dramatic leading the system from regular non chaotic activity to bursting chaotic dynamics induced by by the emergence of correlations in the current fluctuations [4, 5].

References

Plenary 5

Collective Motion: from Bacteria to Drones

Tamás Vicsek∗

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When advancing together, animals or people have to make collective decisions on the move in order to both achieve the given goal of their joint journey as well as stay together because the latter feature has many advantages. It turns out that a few basic ingredients of the decision-making process result in an interesting variety of complex behavioral patterns. In this talk, examples ranging from coherently moving bacteria through birds to robots will be overviewed with the purpose of finding the most common rules underlying the large scale processes during collective motion. Among others, I shall discuss the case when the interactions within a group of animals can be interpreted as corresponding to a hierarchical network of leaders and followers. Such complex social behavior will be demonstrated for the collective motion of homing pigeons. I shall also present a realistic model for collective hunting in a confined environment. At the end of the talk, I shall show examples of how the execution of a global assignment can result in the spectacular flight of a group of unmanned aerial robots.
Plenary 6

Quantifying the Dynamical Complexity of a Time-series from Ordinal Patterns

Antonio Politi

Department of Physics, University of Aberdeen, Aberdeen, UK

Quantifying the complexity of a time series is an important subject of research, especially if this helps distinguishing deterministic chaotic signals from stochastic ones. The Kolmogorov-Sinai entropy is, in principle, an appropriate indicator to look at, but obtaining reliable estimates is problematic even in the case of relatively low-dimensional chaos.

I show that a relevant step forward can be made by combining the analysis of ordinal patterns with the measurement of the width of the corresponding cylinder sets.

Many years ago, Bandt & Pompe [1] suggested to encode finite sequences of data as ordinal patterns, by assigning at each datum within a given window its relative order (largest, second largest, and so on). The corresponding entropy, called permutation entropy, is often used as a proxy for the Kolmogorov-Sinai entropy. However, even in the simple, one-dimensional, logistic map, strong deviations are found between the two quantities for the numerically accessible window lengths.

I propose to look at the dispersion among all trajectories characterized by the same ordinal pattern: a suitably modified “relative” permutation entropy, which takes this information into account [2] allows for far much more accurate estimates even in dynamical systems with multiple positive Lyapunov exponents. The method is illustrated by discussing a few different models, of increasing complexity.

References

Plenary 7

THURSDAY 14:00 – 15:00

Vortex Dynamics: a Journey Through Chemistry and Cardiology

Oliver Steinbock

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Self-organized spatiotemporal patterns include vortex states that can occur in select abiotic reactions but are ubiquitous in the realm of biology. These excitation waves relay desired or detrimental information over macroscopic distances. Most experimental and theoretical studies of these rotors have focused on spatially homogeneous, two-dimensional systems; however, this premise is not valid for living systems that are typically three-dimensional and intrinsically heterogeneous at both the sub- and supra-cellular level. I will discuss recent results on the dynamics of three-dimensional excitation vortices in systems with unexcitable/inert heterogeneities ranging from spheres and cylinders to double-tori and knots. A key feature is the self-wrapping of the rotation backbone (the "filament") to thin heterogeneities [1]. This process re-shapes the wave pattern globally and can stabilize shrinking vortex loops [2]. Another example is the drift of scroll waves in shallow media with a step-like change in height [3]. For three-dimensional systems with turbulent vortex states (caused by negative filament tension), local heterogeneities induce pinned states that expel the turbulent, free filaments. For thick heterogeneities, this process involves the spontaneous formation of vortices with multiple "arms" [4]. While the latter scenarios simplify the wave pattern, knot-shaped heterogeneities can induce a dramatic expansion of the filament. All of these phenomena will be discussed in the context of experiments with the Belousov-Zhabotinsky reaction and numerical simulations of cardiac models.

References

Quantum Chaos in Locally Interacting Lattice Systems

Tomaz Prosen

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Quantum chaos, a field which started in 1980’s from studying quantized single particle models with chaotic classical limit, has recently been reborn from a completely different perspective, namely from studying strongly coupled quantum field theories with AdS/CFT correspondence and holographic gravity duals [1]. Kitaev proposed [2] to study out-of-time-ordered correlations (OTOC) as a universal indicator of quantum chaos and a measure of quantum Lyapunov exponents, which can cover both, the semiclassical and many-body/field-theory physics. I will discuss in particular how quantum lattice models with local interaction, which are generic models of solid state physics, fit into this picture. I will outline a simple toy model which display a clean order to chaos transition, namely kicked Ising spin ½ chain (reviewed in [3]), and discuss its characterization in terms of density of OTOC which displays a feature that can be interpreted as weak quantum chaos [4].

References

Plenary 9

FRIDAY 12:30 – 13:30

Wind Energy with Regard to Nonlinear and Stochastic Dynamics

Joachim Peinke, Gerd Gülker, Michael Hölling, and Matthias Wächter
Institute of Physics and ForWind - Center for Wind Energy Research Carl-von-Ossietzky University Oldenburg, Germany

With an annual installation of more than 50 GW in the last years wind energy has become one of the major renewable energies used world-wide. Based on the experiences of over 1000 years in the use of wind energy made by wind mills, one may be lead to the misjudgment that there are no scientifically challenging questions for the use of wind energy. The main challenges arise from the working conditions of wind turbines, i.e. the nature of wind conditions. As wind turbines are installed in windy places and the energy extraction by the rotor takes place in heights up to 200 m above ground, turbines are working in a highly turbulent environment. Besides the fluctuating features of the energy resource wind, the conversion process of a wind turbine is highly nonlinear by itself.

The question in how far modern wind turbines with diameters larger than 100 m are smoothing out small fluctuations or eventually amplifying them will be discussed. Different aspects of the wind energy conversion dynamics of single turbines and whole wind farms will be discussed. It will be shown how concepts of nonlinear and stochastic dynamics can be fruitfully used for the understanding of wind energy. The intention of this talk is to show that the background of nonlinear and stochastic dynamics is needed to improve the common standardized way of characterization, at the same time the dynamics of wind turbines pose new challenging questions and demands for new basic concepts in analyzing dynamical systems.
Minisymposium talks
**Chemo-hydrodynamics (MS1)**

_Wednesday 8:45 – 10:50 and Thursday 8:45 – 10:50_

_**Organizer:** Marcello A. Budroni_

**Flow Control of $A + B \rightarrow C$ Fronts by Radial Injection**

_Wednesday 8:45 – 9:10 (Room 107)_

_Fabian Brau, Gábor Schuszter, Anne De Wit_

Université libre de Bruxelles (ULB), Brussels, Belgium

Reaction-diffusion (RD) fronts are ubiquitous in a wide variety of phenomena ranging from population dynamics and disease spreading to image processing and nanotechnology to name a few. Among the large family of RD fronts, $A + B \rightarrow C$ fronts are observed when initially separated reactants $A$ and $B$ meet by diffusion and react to produce $C$. Depending on the nature of $A$ and $B$, their dynamics is representative of many problems in chemistry, geochemistry, finance and many others. The temporal evolution of the front position, $x_f$, defined as the location of maximum $C$ production, of the front width $w$ and of the local production rate, $R(x_f)$, have long been derived theoretically [1] and confirmed experimentally [2, 3]. The related scalings $x_f \sim t^{1/2}$, $x_f \sim t^{1/6}$ and $R(x_f) \sim t^{-2/3}$, form the basis of $A + B \rightarrow C$ RD front theory confirmed in many applications.

In flows, $A + B \rightarrow C$ processes provide another important class of dynamics, e.g. in combustion and environmental problems. The coupling between convection and reaction leads to complex dynamics when the flow, actively influenced by transported species, feedbacks on their spatio-temporal distribution. The radial advection of reacting species is currently receiving growing attention. For example, $A + B \rightarrow C$ - type precipitation reactions in a radial flow give rise to a large variety of complex self-assembled structures [5], to thermodynamically unstable crystalline forms [6], or to microstructures significantly different from those obtained in homogeneous systems [7]. Similarly, a suitable redefinition of distance may recast some transport phenomena into a radial spreading as done in studies of infectious disease spreading [8].

Motivated by the broad applications of radial transport in reactive systems, the dynamics of $A + B \rightarrow C$ fronts is analyzed theoretically in presence of passive advection when $A$ is injected radially into $B$ at a constant inlet flow rate $Q$. We compute the long-time evolution of the front position, $r_f$, of its width, $w$, and of the local production rate $R$ of the product $C$ at $r_f$. We show that, while advection does not

Figure 1: Precipitation reaction by radial injection in a confined quasi-2D reactor of a solution of carbonate ions ($A = CO_3^{2-}$) into a solution of calcium ions ($B = Ca^{2+}$) producing calcium carbonate ($C = CaCO_3$). (a) $n_C$, estimated by the intensity $I_{tot}$ of light reflected by $C$, as a function of the volume $V$ of the injected $Na_2CO_3$ solution for various $Q$ and initial concentrations $A_0 = B_0 = 0.2$ M. (b) Slope $\beta$ of the asymptotic linear regime shown in (a) as a function of $Q$ for various $\gamma = B_0/A_0$. 
change the well-known scaling exponents of the evolution of corresponding RD fronts, their dynamics is however significantly influenced by the injection. In particular, the total amount of product, \( n_C \), varies as \( n_C \sim Q^{-1/2}V \), where \( V \) is the volume of injected reactant. This control strategy paves the way to a flow control of the amount and spatial distribution of the reaction front product. It compares well with calcium carbonate precipitation experiments for which the amount of solid product generated in flow conditions at fixed concentrations of reactants can be tuned by varying the flow rate.

References

Sliding Drops from Bifurcations for Single Drops to Ensemble Dynamics

**Uwe Thiele**\(^{1,2}\), **Sebastian Engelnkemper**\(^1\), **Markus Wilczek**\(^{1,2}\), **Walter Tewesand**\(^1\), **Svetlana Gurevic**\(^{1,2}\)

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We study the nonlinear dynamics of liquid drops on homogeneous solid substrates, both, for individual drops (see experiments in [1] and for large drop ensembles. We employ a long-wave evolution equation for partially wetting liquids of small contact angles [2]. After a brief introduction into the modeling of capillarity and wettability in mesoscopic hydrodynamics we focus on the case where the lateral driving due to gravity results in sliding ridges (2d drops) [3] and 3d drops [4].

First, we employ continuation techniques [5] to analyze transformations of periodic trains of stationary sliding droplets (Fig. 1 (left) and (center)). We show that transitions occur at saddle-node bifurcations and discuss a global bifurcation that results in cycles where a sliding droplet emits small satellite droplets at its rear (pearling instability) that subsequently coalesce with the next main droplet. These pearling-coalescence cycles show the period-doubling route to chaos [4]. Second, we numerically simulate the interaction of drop ensembles in large spatial domains. The ongoing coalescence and pearling behavior results in a stationary distribution of drop sizes, whose shape depends on the inclination angle and total liquid volume. We illustrate that aspects of the steady long-time drop size distribution are related to the bifurcation diagram for individual drops. In the final part, this information is employed to construct a coarse-grained statistical model for the time evolution of the drop size distribution. We show that the result well captures the main features of the simulation. In our conclusion we discuss open issues and pose the question whether sliding droplets may actually be considered as another type of dissipative solitons.

![Bifurcation diagram](image)

**Figure 1**: (left) Bifurcation diagram for individual stationary sliding drops (solid and dashed lines) in terms of the drop velocity \( U \) as a function of the inclination angle \( \alpha \) at fixed volume (cf. [4]). (center) Examples of drop profiles from the various sub-branches as indicated by roman numbers. Side branch A consists of pearling-coalescence cycles. (right) Snapshot of droplet ensemble from large-scale simulation.

**References**

Relaxation Oscillations of Solutal Marangoni Convection at Droplets and Chains of Droplet

Karin Schwarzenberger\(^1\), Marcel Mokbel\(^2\), Sebastian Aland\(^2\), Kerstin Eckert \(^1\)

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Mass transfer of surface-active substances across fluidic interfaces is frequently accompanied by Marangoni instability [1]. Marangoni convection can show a temporal periodicity in the form of relaxation oscillations due to subsequent consumption and regeneration of its driving force. Contrary to the complex behavior of strong surfactants or reactive mass transfer, a simple two-phase-system consisting of paraffin oil and water is employed in our study. Due to mass transfer of isopropanol as a weak surfactant, concentration gradients and, by implication, density gradients are produced \textit{in-situ}.

Figure 1: Relaxation oscillations at droplets: experiment (left) and simulation (right).

We have first studied single small droplets, placed in the concentration gradient, by means of a combination of experiments and simulations. The experiments are conducted in a Hele-Shaw experiment in which the droplets are visualized by shadowgraphy [2]. The 2D numerical simulations are based on a diffusive-interface approach and assume a linear concentration and density gradient. We show that the single droplets perform about hundred periods of regular ROs over almost one hour. By analyzing their characteristics, the underlying mechanism can be attributed to the interaction between the mixing by Marangoni convection and the restoring effects of diffusion and buoyant convection on the driving concentration gradients. In the next step, ensembles of droplet comprising droplet pairs as well as linear or circular chains of droplets are investigated. If the spatial distance between the droplets is within the propagation depth of the relaxation oscillations, we observe an excitation of the relaxation oscillation from one droplet to its neighbor [3]. As a result, neighboring droplets are forced to oscillate with the same frequency. On arranging the droplets in chains, an efficient transmission of the relaxation oscillation can be achieved.

References

Effects of Marangoni Flows on $A + B \rightarrow C$ Reaction-diffusion Fronts

Reda Tiani, Laurence Rongy

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When the two reactants of an $A + B \rightarrow C$ reaction are brought into contact, a reaction front is formed and the spatially localized zone where the reaction occurs evolves in time due to the interdiffusion of $A$ and $B$. The properties of such fronts are well studied in reaction-diffusion systems where no flow can affect the dynamics [1, 2]. Here we consider horizontal aqueous solutions where the three species $A$, $B$, and $C$ can affect the surface tension of the solution, thereby driving Marangoni flows (see Fig. 3).

![Figure 1: Focus on the convection rolls centered on the reaction front shown at $t = 30$. The fluid velocity field is superimposed on a 2D plot of the production rate which ranges between its maximum value (reaction front), $ab_{\text{max}}$ shown in red, and its minimum value, $ab_{\text{min}} = 0$, shown in blue. The results are shown for $M_a = M_b = 40$, $M_c = 30$ and $ab_{\text{max}} = 0.050$, where $M_{a,b,c}$ are the Marangoni numbers of each species $A$, $B$, $C$.](image1)

![Figure 2: Classification of the different observed dynamics in the $(M_b, M_c)$ parameter plane at fixed $M_a$. Typical surface tension profiles as well as a sketch of the observed vortex dynamics are illustrated within the corresponding regions. The dark filled arrow indicates the initial direction of propagation of the front. For $M_c < M_a + M_b$ in the shaded regions, we surprisingly observe the possibility of a front reversal (FR), i.e. the front changes its direction in the course of time.](image2)

The resulting dynamics is studied by numerically integrating the incompressible Navier-Stokes equations coupled to reaction-diffusion-convection equations for the three chemical species. We show that the front propagation cannot be predicted anymore on the sole basis of the reaction-diffusion properties as was still possible in the presence of buoyancy-driven flows around such fronts [3]. We relate this observation to
the structure of the Marangoni-driven flow. Based on an analytical description, we propose a classification of the convective effects on $A + B \rightarrow C$ reaction-diffusion fronts as a function of the different Marangoni numbers quantifying the effect of each species on the surface tension [4] (see Fig. 4). We also study the structure of the resulting chemically-driven Marangoni flows.

References

Pattern Formation in Wet Granular Matter

Kay Huang

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From sand dunes to Faraday heaping, driven granular matter, i.e., large agglomeration of macroscopic particles, is rich pattern forming system. When a granular material is partially wet (e.g., wet sand on the beach), a different pattern forming scenario arises due to the cohesive particle-particle interactions [1, 2]. I will introduce how the ‘microscopic’ particle-particle interactions influence the ‘macroscopic’ collective behavior of a mechanically oscillated wet granular layer. In particular, I will focus on the formation of density-wave fronts in an oscillated wet granular layer undergoing a gas-liquid-like transition [3]. The threshold of the instability is governed by the amplitude of the vertical vibrations. Fronts, which are curved into a spiral shape, propagate coherently along the circular rim of the container with leading edges. They are stable beyond a critical distance from the container center. Based on the measurement of the critical distance and the rotation frequency, we propose a model for the pattern formation by considering the competition between the time scale for the collapse of cohesive particles and that of the energy injection resisting this process. Finally, I will discuss the possibility of using mechanical agitations as an additional control for chemical reactions through tuning the collective behavior of catalyst particles.

References

Hydrodynamic Photochemical Oscillators Useful for Chaos Computing

Pier Luigi Gentili

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The convective motions within a solution of a photochromic spiro-oxazine or naphthopyran being irradiated by UV only on the bottom part of its volume, give rise to aperiodic spectrophotometric dynamics [1]. The resulting aperiodic time series have chaotic features as demonstrated by the determination of Lyapunov exponents, correlation dimension, permutation entropy, short-term predictability and long-term unpredictability [2]. The aperiodic time series can be exploited to implement all the fundamental two-inputs binary logic functions (AND, OR, NAND, NOR, XOR, XNOR) and some basic arithmetic operations (half-adder, full-adder, half-subtractor). This is possible due to the wide range of states a nonlinear system accesses in the course of its evolution. Finally, it is possible to build Fuzzy Logic Systems (FLSs) based on the chaotic time series [3]. Such FLSs promise to be useful in the field of Computational Linguistics that is concerned with the development of artificial intelligent systems able to transform collections of numerical data in natural language texts. Therefore, the hydrodynamic photochemical oscillator results promising “wetware” for chaos-computing alternative to conventional CMOS-based integrated circuits.

References

Transient Chaos in Chemically Leaked Open Flows

Izabella Benczik

Eszterházy Károly University Eger, Hungary

Similarly to open chaotic flows that are known to show transient chaos, a chemical leaking can also produce transiently chaotic behavior in closed systems. In the presentation we discuss systems where both factors are present: the flow is open, and the chemical leaking is present. One example of such open flows with biological relevance is that of the blood circulation in which chaotic patterns were identified at sites where the vessel wall has irregularities (narrowing or enlargement). The medical practice associates these sites with enhanced atherosclerotic depositions. Since the atherosclerotic deposition of the platelets can be viewed as a chemical “leaking” from the region of interest, it is clear that the formation of atherosclerotic plaques can be understood only as a joint effect of the two types of leaks: the chemical and the hydrodynamic one. Some nontrivial characteristics of the interplay between the two (chemical and hydrodynamic) leakings are discussed in the talk.

References

Hydrodynamic Instabilities Driven by Complex Chemical Reactions

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Classical hydrodynamic instabilities in Hele-Shaw cells (like those produced by buoyancy or differences in viscosity) [1, 2] have been extensively studied during decades. The potential applications of these subjects have aroused major interest in a variety of research fields with the aim of understanding the physics behind it and thus, find ways to control and model these systems. During the past years, researchers have increased the complexity of these investigations proposing interesting couplings between hydrodynamic instabilities and chemical systems. Accordingly, from simple neutralization reactions [3] or more complicated autocatalytic reactions [4], a broad horizon has been opened where these coupled systems were also extensively analyzed and modeled seeking the description of new instabilities. In the present contribution, two setups will be analyzed that clearly demonstrate the constructive role played by the coupling of chemical and hydrodynamic instabilities. Firstly, we present a system in which a buoyancy-driven instability is generated due to the oscillatory Belousov-Zhabotinsky reaction [5]. Secondly, a pH-shifting reaction which produces a new type of viscous finger instability [6]. In both cases, the control parameters are varied in order to analyze the origin of the new instability. Additionally, we use advanced optics techniques and numerical simulations as a complementary source of information in order to unveil the mechanisms underlying behind the observed phenomena.

References

Laminar Mixing in Tubular Networks of Plasmodial Slime Moulds

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The plasmodium of the unicellular slime mould Physarum polycephalum forms an extended vascular network, which is used for transportation of protoplasm through the giant cell. The transport is driven by pressure gradients generated by peristaltic pumping, leading to a flow that reverses its direction periodically. Although the flow in the veins of P. polycephalum is always parabolic, protoplasm and particles suspended in it are effectively and rapidly distributed within the cell. To elucidate how an effective mixing is achieved in such a microfluidic system with Poiseuille flow (at low Reynolds and Womersley numbers), we performed micro-PIV experiments and advect virtual tracers in the determined time-dependent flow fields. Flow splitting and flow reversals at branchings of veins, as well as small fluctuations in the flow patterns at the branchings of veins play key roles in providing for an efficient mixing of protoplasm in the cell.
The Interplay Between Solute Mixing and Chemical Reaction in 2D Porous Media

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The mixing and reactive transport of chemical elements and nutrients is a primary controlling process for biogeochemical cycles and contaminant transport in subsurface environments. Reaction kinetics measured in well-mixed laboratory reactors are much larger than those encountered on the field, and Darcy-scale models based on Fickian transport/mixing often cannot explain field measurements. This is attributed to the heterogeneity of the pore scale velocity field in porous media, and to the interplay, at pore scale, between this heterogeneous advection, molecular diffusion, and (homogeneous) chemical reactions. Pore scale characterization of flow velocities and of the spatial distribution of solute concentrations is a key to understanding this complex interplay. We use two-dimensional micromodels to investigate it in transparent porous media consisting of a Hele-Shaw cell containing cylindrical grains, at the pore scale. The media are made by lithography with full control on a geometry containing thousands of grains. The setup allows for unsaturated flows, be it primary drainage/imbibition, or the injection of two fluids (f. e. water and air) at the same time. A camera positioned above the flow cell records the distributions of fluid phases, at regular times, providing also the position of solid tracers and spatially-resolved images of light emissions inside the flow cell. The pore scale velocity field is measured from the tracking of solid tracers (microspheres), while pore scale concentration fields are measured accurately in passive transport experiments, using fluorescein and converting the emitted light intensities into solute concentrations. Pressure drops across the medium are also measured. This complete characterization of the system allows confronting the experimental pore scale data to numerical simulations and models that upscale transport and mixing properties. Using a chemo-luminescent reaction, which produces photons in addition to the reaction product, we can measure the local production rate of the reaction product as the reactive liquids flow through the system and mix. We address this configuration under mixing-limited conditions (very large Damköhler number) [1], confronting the data to numerical simulation and models based on the lamellar structure of the mixing zone [2]. We also discuss the case of mixing in an unsaturated medium, for which the presence of air constrains the topology of the flow and consequently the local reaction rates between transported species [3, 4].

References
Chemobrionics: Fluid Dynamics and Complexity (MS2)

Organizers: Silvana Cardoso, Julyan Cartwright, Gábor Schuszter

Self-mixing in the Earths Atmosphere, Oceans, and Subsurface

Silvana Cardoso

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Chemical and physical disequilibrium in the Earths oceans, atmosphere and subsurface can lead to gigantic convective flows of methane and carbon dioxide. Examples in the atmosphere and oceans include the turbulent plumes formed during the Icelandic volcanic eruption (2010) and the large number of methane plumes found recently in the Arctic Sea (2013). In the sub-surface, when carbon dioxide dissolves in the water contained in the porous rock, the heavy CO$_2$-rich fluid sinks driving vigorous laminar convection [1]. A further example is the flow of dissolved methane under osmotic forces in the porous rock near mud volcanoes on the seabed [2]. In this talk, we focus on how the interaction between hydrodynamics and chemistry can drive fluid flow, including examples that are thought to be of relevance for the origin of life [3].

References

The Spark of Life: The Physics of How the Earth Went From Geology and Chemistry to Biology

Julyan Cartwright

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More than 3.5 billion years ago, something interesting happened on Earth. Somewhere matter self-organized so that it was able to reproduce its complex state. Life had begun. Where and how that happened are questions whose answers, after many centuries, seem at last within reach. About four decades ago there were discovered hydrothermal vents at the bottom of the oceans; for 25 years there has been increasing evidence that they were the cradle of life on Earth. We shall examine how physics can help explain how life started.
Comparison of Flow-controlled Calcium and Barium Carbonate Precipitation Patterns for Underground Carbon Dioxide Sequestration

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Injection of carbon dioxide in porous aquifers, where mineralization takes place via chemical reactions, is one possible long-term solution considered for storage of this greenhouse gas. However, such a flow-driven precipitation may dramatically change the porosity and permeability of the host medium, possibly leading to pore clogging. As in situ experiments on real geological formations are difficult, it is of interest to perform laboratory studies of mineralization in real reservoir samples. X-ray data can give access to the 3D structure of the solid carbonate precipitates. Thanks to an enhanced contrast of barium with regard to calcium in X-ray analysis, it is of interest to understand whether the spatial distribution and amount of barium carbonate precipitates are similar or not to the calcium carbonate ones to assess whether X-ray studies based on barium are representative of those with calcium or not. To get insight into this problem, we analyze here experimentally related precipitation patterns in a confined 2D geometry [1]. The mineralization is investigated by injecting radially a solution of sodium carbonate in a quasi 2D Hele-Shaw cell, mimicking porous media, initially filled with a solution of either calcium or barium chloride. Various precipitation patterns like spirals, fingers, tubes, etc. are obtained during injection due to the coupling of chemistry and hydrodynamics. The pattern properties are quantified to analyze the influence of growth conditions on mineralization [2]. We show the existence of critical concentrations of reactants, which are functions of flow rate, above which the amount of precipitate drops significantly even if the reactant concentrations are large in the vicinity of the reaction zone. We also compare the calcium and barium carbonate precipitate structures obtained as a function of initial concentrations and injection flow rate. We show that, in some part of the parameter space, the calcium and barium carbonate patterns are similar and feature comparative properties indicating that barium and calcium behave similarly in the related flow-controlled precipitation conditions. For other values of parameters though, the precipitate structures are different indicating that the cohesive and microscopic properties of barium versus calcium carbonate are there important in shaping the pattern in flow conditions [3].

References

Chemobrionics Meets Microfluidics: Control of Growth Dynamics and Prebiotic Processes

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We discuss recent efforts to control the growth of chemical gardens (hollow tubes of inorganic materials) and related self-organized structures. Examples include the delivery of the reactant solutions at constant flow rates or alternatively constant pressure, spatial confinement to quasi-two-dimensional layers, and the growth of linear membranes in microfluidics device that initially create a reactive interface via a laminar flow. We also present new results on prebiotic chemical processes in three-dimensional chemical gardens that suggest how simple organic acids, alcohols, and sugars (including ribose) might have formed on the early Earth in alkaline hydrothermal vents.
Experimental Investigation of Turbulent Plumes with a Precipitation Reaction

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A large number of methane plumes have been recently detected in the Arctic Sea. These plumes originate from deep-ocean releases of buoyant methane. At sufficiently large depth and low temperature, however, methane reacts with seawater forming insoluble methane hydrates. The hydrate-formation reaction affects the bulk density of the rising fluid in a methane plume. Hence, the motion and eventual fate of the chemical species contained in the plume depend critically on the rate of internal buoyancy changes caused by the formation and dissolution of methane hydrates. We present a series of new laboratory experiments, in which the precipitation of barium sulfate, from aqueous solutions of barium chloride and sodium sulfate, is used as an analogue of the formation of methane hydrates in a methane plume. In our experiments, the density of the plume fluid at the source and the concentration of the chemical species in the plume and in the ambient fluids are varied to investigate the combined impacts of the precipitation reaction and the turbulent motion of the flow. An image analysis technique is used to quantify the steady-state concentration of particles in the plume fluid as a function of distance from the source. A quantitative model is developed to estimate this concentration, which depends on both the rate at which particles are formed by the reaction and the rate of dilution of the plume fluid. The model predictions are successfully tested against the results of the experiments.
Complex Networks: Delays and Collective Dynamics (MS3)

Organizers: Yuliya Kyrychko and Konstantin Blyuss

Control of Chimeras by Time Delay in Dynamical Networks

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We investigate the influence of time-delayed coupling in a ring network of non-locally coupled Stuart-Landau oscillators upon chimera states, i.e., space-time patterns with coexisting partially coherent and partially incoherent domains. We focus on amplitude chimeras \cite{Zakharova2014}, which exhibit incoherent behavior with respect to the amplitude rather than the phase, and are transient patterns, and show that their lifetime can be significantly enhanced by coupling delay. To characterize their transition to phase-lag synchronization (coherent traveling waves) and other coherent structures, we generalize the Kuramoto order parameter. Contrasting the results for instantaneous coupling with those for constant delay, for time-varying delay, and for distributed delay coupling, we demonstrate that the lifetime of amplitude chimera states and related partially incoherent states can be controlled, i.e., deliberately reduced or increased, depending upon the type of coupling delay \cite{Scholl2016}.

References

Local Bifurcations in Delay Equations with State-dependent Delays

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Delay-differential equations (DDEs) with state-dependent delays suffer from a lack of regularity: even if all coefficients in the equations are apparently smooth, the dependence of the solution on the initial conditions is not continuously differentiable more than once in any of the known choices for phase space. We show that local center-unstable manifolds near equilibria can still be as smooth as the spectral gap in the linearization permits. This result makes many ready-to-use normal form transformation formulas developed by Govaerts, Kuznetsov et al. for ordinary differential equations (recently extended to DDEs with constant delays) applicable to DDEs with state-dependent delays. We give a first demonstration how normal form coefficients can be obtained for a Hopf bifurcation in a scalar DDE with several nesting levels for the delays.
Generation and Propagation of Delay-induced Extreme Events in Spatially Extended Systems

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Extreme events are rare, recurrent and aperiodic events which have a large impact on the dynamical system. The study of such extreme events has gained increasing attention in recent years due to its ubiquitous appearance in a wide variety of important physical situations ranging from natural disasters to financial crises. Such studies have led to the identification of many crucial factors which contribute to the emergence of such events which include progressive spatial synchronization, chaotic pulse bunching and an interior crisis in networks of non-identical relaxation oscillators. However, the study of the role of time-delay in the generation and propagation of extreme events remains limited. Although time-delayed systems are known to generate extreme events experimentally, the underlying mechanism of the emergence of delay-induced extreme events remains unknown.

Firstly, we discuss our recent investigations on the role played by time-delays in the generation and propagation of extreme events in excitable systems. We first consider a pair of identical FitzHugh-Nagumo (FHN) oscillators and couple them by diffusive delay coupling. Since in real world networks of excitable systems, individual units might be connected to each other via more than one route – each characterized by its own connection strength and time delay – we allow the FHN units in our model to be coupled with multiple delays. We demonstrate that such a system is capable of generating extreme events and investigate the role of the structure of the infinite dimensional phase space and its invariant manifolds in the generation of extreme events. We finally show that due to an intricate dynamics of the invariant manifolds, the parameter region where extreme events are feasible is sandwiched between regions of period-adding and period-doubling cascades. Moreover, the extreme events generated can be classified distinctly by two categories of synchronous and asynchronous events.

Secondly, we present initial results from our ongoing investigations on propagation of extreme events through a spatially extended network. To that end, we construct a delay-coupled network in which we place a pair of coupled FHN units – capable of generating extreme events – on each node. By changing the intra-node coupling parameters, we set each node in the network in a way such that in absence of any inter-node coupling, a fraction of them exhibit extreme events. When coupled, the resulting dynamics depends on the inter-node coupling parameters as well as network topology and size. We investigate if extreme events can be induced or quenched by the interaction of the nodes. Finally, we present our initial simulation results which show the possibility of emergence of entirely new dynamical regimes.
Bifurcations Mediating Appearance of Chimera States

Oleh Omel’chenko

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Coherence-incoherence patterns, better known as chimera states, are complex dynamical regimes observed in spatially homogeneous systems of nonlocally coupled oscillators. In many cases they can be adequately represented by relatively simple solutions, e.g. rotating or traveling waves, of a certain partial integro-differential equation. Bifurcation analysis and continuation of these solutions is usually a difficult problem, because of the critical continuous spectrum of the corresponding linearized operator. In this talk, I will discuss mathematical challenges concerned with the consideration of chimera states and show their possible solution in a few special cases motivated by recent research in the field.
Time-delayed Model of RNA Interference

Konstantin Blyuss

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RNA interference is a fundamental cellular process responsible for a number of important functions, from immune defense to regulation of development and morphogenesis. In this talk I will discuss a mathematical model of RNA interference with a particular account for time delays associated with primed amplification. I will present analytical and numerical results of stability analysis for various states of the model and discuss their biological significance. I will demonstrate how time delays can affect bi-stability associated with the hysteresis loop in the system. Numerical results will illustrate various types of behavior, including simultaneous co-existence of a stable steady state and a stable periodic orbit.
Complex Patterns on Networks (MS4)

Organizers: Jan F. Totz, Erik Martens, Ralph G. Andrzejak

Chimeras in Networks with Complex Topologies

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Chimera states are an example of intriguing partial synchronization patterns emerging in networks of identical oscillators. They consist of spatially coexisting domains of coherent (synchronized) and incoherent (desynchronized) dynamics. We analyze chimera states in networks of Van der Pol oscillators with hierarchical (fractal) connectivities [1]. We investigate the stepwise transition from a nonlocal to a hierarchical topology, and propose the network clustering coefficient as a measure to establish a link between the existence of chimera states and the compactness of the initial base pattern of a hierarchical topology; we show that a large clustering coefficient promotes the occurrence of chimeras. Depending on the level of hierarchy and base pattern, we obtain chimera states with different numbers of incoherent domains. We investigate the chimera regimes as a function of coupling strength and nonlinearity parameter of the individual oscillators. We also elaborate the role of time delay introduced in the coupling term [2]. In the parameter plane of coupling strength and delay time we find tongue-like regions of existence of chimera states alternating with regions of existence of coherent traveling waves. We demonstrate that by varying the time delay one can deliberately stabilize desired spatio-temporal patterns in the system.

References

Time-delayed Feedback Control of Noise-induced Chimera States

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We show that chimera patterns can be induced by noise in nonlocally coupled neural networks in the excitable regime. In contrast to classical chimeras, occurring in noise-free oscillatory networks, they have features of two phenomena: coherence-resonance and chimera states. Therefore, we call them coherence-resonance chimeras [1]. These patterns demonstrate the constructive role of noise and appear for intermediate values of noise intensity, which is a characteristic feature of coherence resonance. In the coherence-resonance chimera state a neural network of identical elements splits into two coexisting domains with different behavior: spatially coherent and spatially incoherent, a typical property of chimera states. Interestingly, these noise-induced chimera states are characterized by alternating behavior: coherent and incoherent domains switch periodically their location. We show that this alternating switching can be explained by analyzing the coupling functions [2]. Moreover, we investigate the impact of time delay on coherence-resonance chimeras and demonstrate that time delay can be used to control the noise-induced chimera states. In more detail, the interval where coherence-resonance chimeras exist can be significantly increased by introducing time-delayed feedback.

References

Driver Response Couplings Between Networks in Chimera States

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Despite having a simple structure, networks of coupled oscillators can show an intriguing complex dynamics. They can segregate into complimentary groups and exhibit a chimera state. While a group of oscillators jointly rotates coherently at an almost constant phase velocity, the oscillators of the other group perform an erratic motion. There is growing experimental and conceptual evidence that chimera states are relevant for real-world networks. Networks in the real world, however, are typically not isolated. Instead they are connected to other networks. It is therefore important to study interactions between separate networks exhibiting chimera states. We here study a drive response dynamics of separate networks, where each individual network is in a chimera state. We use the auxiliary system approach to show that generalized synchronization can be induced between the drive and response network. We show that identical synchronization is established if and only if drive and response are identical. In both forms of synchronization the driver and response network continue to show chimera states.
Control of Chimera States Via Pacemakers

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Chimera states are intriguing dynamics that arise in networks of coupled oscillators. In a chimera state, synchronous and asynchronous behaviors coexist. Such dynamics have been observed not only in models but also in real-world scenarios. Recent studies have considered the possibility of controlling the chimera state. This control can concern the position of the asynchronous group in the network. Likewise, it can aim at generating chimeras for parameter settings for which no chimeras arise without control. For example, in a 2016 paper by Isele et al. \cite{Isele2016}, control in both these aspects was achieved in networks of FitzHugh-Nagumo oscillatory units via the insertion of a barrier of excitable units. We address the problem of controlling the chimera state in the basic setting of phase oscillator networks. Breaking the symmetry of the system with a pacemaker oscillator we obtain results analogous to the ones presented by Isele and colleagues \cite{Isele2016}. We show that this simple mechanism allows one to control the position of the incoherent group of oscillators which is centered on the pacemaker. Furthermore, the presence of a pacemaker provokes a chimera state for values of the network parameters that normally do not allow for the formation of a chimera.

References

Chimera States in Nonlinear Systems with Delayed Feedback

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Due to their infinite-dimensional phase space, delay dynamical systems modeled by delay differential equations (DDE) can exhibit very complex behavior. Recently, a new class of nonlinear DDE involving a second order differential model has received a growing interest. Describing an optoelectronic setup in our case, model provides qualitatively new solutions compared to conventional scalar DDE (Ikeda or Mackey-Glass dynamics) [1,2].

In this contribution we report the first observation of so-called chimera states in optoelectronics [3]. Chimera states are characterized by spontaneous symmetry breaking when viewed in a space-time representation [4]. The dynamical system of concern is governed by an Ikeda-like DDE including an integral term:

\begin{equation}
\varepsilon \dot{x} = -x - \delta \int_{t_0}^{t} x(\xi) d\xi + \beta f[x(t-\tau)]
\end{equation}

where \( \varepsilon \) and \( \delta \) are typically small bifurcation parameters, \( \beta \) is the third control parameter, and \( f \) is some function describing the nonlinear delayed feedback of the dynamics. In our optoelectronic setup, \( f \) is provided by the wavelength-to-intensity nonlinear transformation obtained from a Fabry-Pérot interferometer, i.e.

\[ f(x) = \left[1 + m \sin^2(x + \Phi_0)\right]^{-1}, \quad m \simeq 4.2, \quad \Phi_0 \simeq -0.4. \]

We report on the particular bifurcation scenario for the chimera states appearance as \( \beta \) increases, observed both numerically and experimentally. It is crucial to mention that chimeras in the system described by Eq. (1) are highly robust, i.e. they can be observed for a wide range of parameters and are stable with respect to the noise in the experimental setup.

References

Patterns on a Starvation Network: Aggregation and Fruiting Body Formation in Soil Bacteria

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Cells, biological tissues, highly coordinated animal groups and interacting populations are a form of complex networks with emergent coherent properties that arise from mechanical and socially-mediated interactions between individuals. Unlike in purely physical systems, a biological individual is capable of processing information, in addition to tuning dynamically adaptive response. These augmented capabilities of individual units allow a population to exhibit collective organization and behavior, beyond what is found in traditional networks. I will present this perspective using the aggregation and fruiting body formation of the soil bacterium, *Myxococcus Xanthus* as an example. I will first show how this process of aggregation can be understood as a non-equilibrium phase separation using theoretical ideas from active matter physics. I will then discuss a regime where theory and experiment differ and show how these differences arise due to the formation of dynamic communication networks between the bacteria. These networks are formed due to the motion and transient contact of the bacteria with each other, triggering genetic and molecular regulation in the bacterial population. Finally, I will speculate how such communication by contact and aggregation might relate to ecological and evolutionary consequences of the bacterial life cycles.
Noise-induced Patterns in Networks of Adaptive Excitable Elements

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Excitable systems that generate all-or-none responses are ubiquitous. A prominent example are neurons that generate action potentials, also called spikes, in response to noisy inputs such as synaptic input and sensory input from receptor cells. On long time scales, spike generation is modulated by slow feedback processes, resulting from intrinsic adaptation currents, fluctuations of external ion concentrations or from synaptic plasticity in neural networks. In this context, we study how network dynamics is influenced by the interplay of noise and feedback. As a model system we consider the action potential generation in certain sensory neurons that possess myelinated distal dendritic tree-like arbors with excitable nodes of Ranvier at peripheral and branching nodes.

In the absence of feedback, connected excitable elements show coherent oscillations. We observe several noise-induced phenomena such as array-enhanced coherence resonance, spiking becomes most regular at a finite coupling strength, and system-size coherence resonance, spiking becomes most regular at a finite network size [1,2]. We develop a theory for coherent network oscillations. Our theory predicts how network properties and the intrinsic feedback of individual elements affects the network dynamics. In the presence of excitatory feedback, the interplay of noise and feedback leads to complex spiking patterns during which individual excitable elements switch between periods of fast regular spiking and slow irregular spiking. This behavior is sensitive to network properties as well as the noise intensity and is reminiscent of the phenomenon of noise-controlled bistability, which so far has only been reported for single excitable elements subject to slow feedback [3].

References

Long-range Interactions, Wobbles, and Phase Defects in Biological Oscillator Networks

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Eukaryotic cilia and flagella are chemo-mechanical oscillators capable of generating long-range coordinated motions known as metachronal waves \cite{1}. Pair synchronization is a fundamental requirement for these collective dynamics \cite{2}, but it is generally not sufficient for collective phase-locking, chiefly due to the effect of long-range interactions. Here we explore experimentally and numerically a minimal model for a ciliated surface: hydrodynamically coupled oscillators rotating above a no-slip plane \cite{3}. Increasing their distance from the wall profoundly affects the global dynamics, due to variations in hydrodynamic interaction range. The array undergoes a transition from a traveling wave to either a steady chevron pattern or one punctuated by periodic phase defects. Within the transition between these regimes the system displays behavior reminiscent of chimera states.

Figure 1: (a) Spherical colloidal particles are held at a fixed distance $h$ above a no-slip boundary, and driven in circular trajectories by time-sharing optical tweezers. (b) Kymographs showing the phase along the linear array of colloidal oscillators driven by OTs. (c) Deterministic numerical simulations of spherical colloids above a no-slip wall, interacting hydrodynamically through the Blake tensor.

References

Tweezer Control for Chimera States

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Chimera states are complex spatiotemporal patterns consisting of coexisting domains of coherent and incoherent dynamics. We study chimera states in small networks of nonlocally coupled oscillators. Usually, small size of the networks makes observation of chimera states difficult due to their short lifetime and erratic drifting of the spatial position of the incoherent domain. We propose a Tweezer control scheme which can stabilize and fix the position of chimera states in small networks [1]. Our control is an interplay of two instruments, the symmetric control term suppresses the chimera collapse, and the asymmetric control effectively stabilizes the spatial position of chimera states.

We demonstrate the effective work of the Tweezer control scheme in small networks of Van der Pol and FitzHugh-Nagumo oscillators. We uncover optimal values for the control gains of two parts of the Tweezer control for the most efficient stabilization of chimera states.

References

Spatio-temporal Propagation of Perturbation in Complex Networks

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Recent advances in network theory enable us to study the interplay between the topological structure and the intrinsic dynamic states of all nodes. Here we track the spatio-temporal patterns of propagation of information along the network, such as the spreading of diseases, the response to a genetic perturbation or the onset of collective synchronization. [1-3]. We analytically derive the response propagation, obtaining its dependence on the degree distribution, the distance from the perturbation and the intrinsic dynamics of each network. Our results uncover a deep universality in the propagation patterns crossing domains of inquiry, from disease spreading to technological failures and gene regulatory dynamics.

References

Complicated Dynamics and Chaos in Cell Systems (MS5)

Organizer: Marek Kimmel

Coupling the Mammalian Cell Cycle to the Circadian Clock: From Entrainment to Complex Oscillations and Chaos

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The cell division cycle and the circadian clock represent two major cellular rhythms. These two periodic processes are coupled in multiple ways, given that several molecular components of the cell cycle network are controlled in a circadian manner. For example, in the network of cyclin-dependent kinases (Cdks) that governs progression along the successive phases of the cell cycle, the synthesis of the kinase Wee1, which inhibits the G2/M transition, is enhanced by the complex CLOCK-BMAL1 that plays a central role in the circadian clock network. Another component of the latter network, REV-ERB, inhibits the synthesis of the Cdk inhibitor p21. Moreover, the synthesis of the oncogene c-Myc, which promotes G1 cyclin synthesis, is repressed by CLOCK-BMAL1. Using detailed mathematical models for the two cellular regulatory networks we investigate the conditions in which the mammalian cell cycle can be entrained by the circadian clock. We show that the cell cycle can be brought to oscillate at a period of 24h or 48h when its autonomous period prior to coupling is in an appropriate range. The model indicates that the combination of multiple modes of coupling does not necessarily facilitate entrainment of the cell cycle by the circadian clock. Outside the range of entrainment, the coupling to the circadian clock may lead to disconnected oscillations in the cell cycle and the circadian system, or to complex oscillatory dynamics of the cell cycle in the form of endoreplication, complex periodic oscillations or chaos. An extension of the model shows that bidirectional coupling of the cell cycle to the circadian clock can lead to mutual entrainment, complex periodic oscillations or chaotic dynamics.

References

Games with Resources in Modeling of Cancer Cell Interactions

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In this study we propose to endow evolutionary game models with changes of the phenotypes’ adjustment during the transient generations within the population. These changes are performed by the parameters in the payoff matrix, which determine the fitness (payoff, adjustment) resulting from different interactions between players (taking into account both the benefits and costs of particular actions and strategies). Alteration of these parameters changes them into functions that simulate (within this model) the changes within the environment and define their different impacts on the fitness. In the case of spatial games, these functions are represented by an additional lattice where another and parallel game based on cellular automata is performed. The main assumption of the spatial games presented in [1] is that each cell on the lattice is represented by a player following only one strategy. The local payoff for each player is the sum of payoffs due to interactions (according to the payoff matrix) with cells in the neighborhood. We will refer to this approach as the classical one or SEGT. Cells on the spatial lattice can also be considered as heterogeneous (instead of homogeneous), so that each particular player may contain mixed phenotypes. Spatial games of the type proposed by us in [2] are called mixed spatial evolutionary games (MSEG). Hence, in MSEG different degrees of playing a particular strategy are treated as different characteristics that define different phenotypes. It may happen that within the population, all of the players have diverse phenotypes (which probably better describes biological phenomena). In fact, the game is performed on a multidimensional lattice (dependent on the number of defined phenotypes in the model), where each layer represents a particular phenotype (as the frequency of occurrence) of the player. For the computation of the local adaptation, the sum of the payoffs between each phenotype (within two players) multiplied by their rate of occurrence is calculated first. The second step is the summing of these values for each player in the neighborhood. The proposed modification which takes into account changes in the generalized resources (SEGR) needs yet another additional lattice to be used. It is equivalent to the increased order of dynamics considered in replicator dynamics. The important implication is that even in the case of three phenotypes when the order of replicators dynamics is two, introduction of resources increases an order of dynamics to three which, because of its nonlinearity, allows to expect possibly complex phenomena.

References

Experimental and Theoretical Analysis of the Coupling between the Mammalian Cell Cycle and Circadian Clock Oscillators


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Most organisms have evolved a circadian timing system to adapt their physiology and behavior to the daily environmental changes resulting from the rotation of the earth on its axis. This is achieved through a self-sustained oscillatory gene network present in virtually all cells and which temporally coordinates a plethora of molecular, cellular and physiological processes. Interestingly, daily synchronous rhythms of cell division are observed in many species ranging from cyanobacteria to humans. This strongly suggests that the molecular circadian clock and the cell cycle machinery are functionally connected. Consistently, several molecular links have been uncovered during the last 10 years indicating that the circadian clock and cell cycle are coupled oscillators. Despite this mechanistic knowledge, little is known regarding the dynamics of this coupling and how the temporal organization of cell division at the single cell level produces the daily rhythm at the tissue level. Using multispectral fluorescent imaging of genetically modified single live cells, computational methods and mathematical modeling we addressed this issue in proliferating mouse fibroblasts. This approach revealed that in unsynchronized cells, the cell cycle and circadian clock robustly phase-lock each other in a 1:1 fashion so that in an expanding cell population the two oscillators oscillate in a synchronized way with a common frequency. Pharmacological synchronization of cellular clocks reveals additional phase-locked clock states. The temporal coordination of cell division by phase-locking to the clock at a single cell level has significant implications because disordered circadian function is increasingly being linked to the pathogenesis of many diseases including cancer.

References

Model-based Investigation of the Circadian Clock and Cell Cycle Coupling in Mouse Embryonic Fibroblasts: Prediction of RevErb-α Up-regulation during Mitosis

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Experimental observations have put in evidence autonomous self-sustained circadian oscillators in most mammalian cells, and proved the existence of molecular links between the circadian clock and the cell cycle. Some mathematical models have also been built to assess conditions of control of the cell cycle by the circadian clock, with applications to cancer chronotherapy optimization [1]. However, recent studies in individual NIH3T3 fibroblasts have shown an unexpected acceleration of the circadian clock together with the cell cycle when the culture medium is enriched with growth factors, and the absence of such acceleration in confluent cells [2]. In order to explain these observations, we have studied a possible entrainment of the circadian clock by the cell cycle through a regulation of clock genes around the mitosis phase. We developed a computational model in Biocham [3] with a formal specification of the observed behavior in quantitative temporal logic [4,5] to investigate the conditions of entrainment in period and phase. We showed that either the selective activation of RevErb-α or the selective inhibition of Bmal1 transcription during the mitosis phase, allowed us to fit the experimental data on both period and phase, while a uniform inhibition of transcription during mitosis seems incompatible with the phase data [6]. We conclude on the arguments favoring the RevErb-α up-regulation hypothesis and on some further predictions of the model.
Mathematical Modelling Reveals Unexpected Inheritance and Variability Pattern of Cell Cycle Parameters in Mammalian Cells

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Knowledge of inheritance and variability patterns of mammalian cells can help predict behavior of subsequent generations of cells and address cell homeostasis and regulation, in variable environment. In this work, we focus on the cell cycle to analyze such relations. Our research is based not only on the information about cell cycle duration, but also on protein dynamics. We use single-cell protein expression data collected from murine NIH 3T3 cells using a stable FUCCI system. To fit the data we used the bifurcation autoregression model coupled with differential equations for protein dynamics. Resulting model fits very well the experimental results. An interesting finding is that the variability of the DNA-synthesis time contributes a major portion of the cell cycle length variability, contrary to the common view that it is the G1 phase that varies most. Questions we address include the long-term predictability of cell cycle dynamics. Long-term simulations of the model reveal a pattern of ”dynamic homeostasis”, involving cell cycle lengths and protein levels oscillating within a controlled range. Our simulations generate predictions of dynamics of free-growing cell populations, which await experimental confirmation. We also compare the resulting dynamics to that of our previous models.
Extracting Fractal and Extreme Aspects from Series of Random Dynamical Systems

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Extracting chaotical ([2]) and stochastic parts of information from time series needs very specific techniques. Motivated by two applications, image processing for cancer discrimination (see [9]) and methane emissions modeling (see e.g. [3, 4, 6]) we will explain the necessary techniques for statistical learning on chaotical and stochastic parts from data. In particular, Tsallis Entropy will be introduced and its role in information theory for dynamical system explained. Iterated function systems will be used as an example for chaos re-simulation (see e.g.[8]). In particular, a construction of stochastic fractals will be discussed. All can be well integrated to both natural and technical sciences, which gave us an optimal instrument for the decomposition of data to stochastic, deterministic and chaotic part (see [10]). In particular, several important issues regarding cell cycle dynamics will be given. The correlation dimension algorithm used by [7] is not a good choice, since albeit the method is algorithmizable, it is not possible to use it for any comparisons (and in particular for calibration with real data), since is not satisfying so called monotonicity condition. This monotonicity condition states that dim(Cµ) = dim(µ) for invariant measure _ and any constant C > 0; (roughly speaking dimension is remaining unchanged when measure is probabilized (or multiplied by some positive constant), which is clearly not satisfied by correlation dimension. Modified corr. Dimension, which is monotonous, was proposed from theoretical construction by [5]. However, algorithmization should be developed.

References

Thick Distribution Tails and Super-exponential Growth in Models of Cancer Secondary Tumors

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Due to progress in microdissection and in DNA sequencing, it became possible to subsample multi-focal tumors in organs such as liver in several hundred spots and determine the pattern of mutations in each of these spots. This has led to construction of genealogies of the primary, secondary, tertiary and so forth, foci of the tumor. These studies led to diverse conclusions concerning the Darwinian (selective) or neutral evolution in cancer. Mathematical models of development of multifocal tumors have been developed to support these claims. We report a model of development of a multifocal tumor, which is a mathematically rigorous refinement of a model of Ling et al. recently published in the PNAS. We show that the rigorous model, in the form of an infinite-type branching process, displays distributions of tumors size which have infinite expected values and which may grow super-exponentially. Aside of mathematical interest, this model is corroborated by recent reports of possibly super-exponential growth in cancer metastases.
Covariant Lyapunov Vectors and Applications (MS6)

Organizers: Juan M. López and Valerio Lucarini

Statistical and Dynamical Properties of Covariant Lyapunov Vectors in a Coupled Atmosphere-ocean Model

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We study a simplified coupled atmosphere-ocean model using the formalism of covariant Lyapunov vectors (CLVs), which link physically-based directions of perturbations to growth/decay rates. The model is obtained via a severe truncation of quasi-geostrophic equations for the two fluids, and includes a simple yet physically meaningful representation of their dynamical/thermodynamical coupling. The model has 36 degrees of freedom, and the parameters are chosen so that a chaotic behavior is observed.

One finds two positive Lyapunov exponents (LEs), sixteen negative LEs, and eighteen near-zero LEs. The presence of many near-zero LEs results from the vast time scale separation between the characteristic time scales of the two fluids, and leads to nontrivial error growth properties in the tangent space spanned by the corresponding CLVs, which are geometrically very degenerate. Such CLVs correspond to two different classes of ocean/atmosphere coupled modes.

The tangent space spanned by the CLVs corresponding to the positive and negative LEs has, instead, a non-pathological behavior, and one can construct robust large deviations laws for the finite time LEs, thus providing a universal model for assessing predictability on long to ultra-long scales along such directions. Interestingly, the tangent space of the unstable manifold has substantial projection on both atmospheric and oceanic components.

The results underline the difficulties in using hyperbolicity as a conceptual framework for multiscale chaotic dynamical systems, whereas the framework of partial hyperbolicity seems better suited, possibly indicating an alternative definition for the chaotic hypothesis. They also suggest the need for accurate analysis of error dynamics on different time scales and domains and for a careful setup of assimilation schemes when looking at coupled atmosphere-ocean models.

References

Characterising Blocking-like Events in a Quasi-geostrophic Model with Covariant Lyapunov Vectors

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One of the most relevant weather regimes in the mid-latitudes atmosphere is the persistent deviation from the approximately zonally symmetric jet stream to the emergence of so-called blocking patterns. Such configurations are usually connected to exceptional local stability properties of the flow which come along with an improved local forecast skills during the phenomenon. It is instead extremely hard to predict onset and decay of blockings.

Covariant Lyapunov Vectors (CLVs) offer a suitable characterization of the linear stability of a chaotic flow, since they represent the full tangent linear dynamics by a covariant basis which explores linear perturbations at all time scales. Therefore, we assess whether CLVs feature a signature of the blockings. As a first step, we examine the CLVs for a quasi-geostrophic beta-plane two-layer model in a periodic channel baroclinically driven by a meridional temperature gradient $\Delta T$. An orographic forcing enhances the emergence of localized blocked regimes. We detect the blocking events of the channel flow with a Tibaldi-Molteni scheme adapted to the periodic channel. When blocking occurs, the global growth rates of the fastest growing CLVs are significantly higher. Hence, against intuition, the circulation is globally more unstable in blocked phases.

Such an increase in the finitetime Lyapunov exponents with respect to the long term average is attributed to stronger barotropic and baroclinic conversion in the case of high temperature gradients, while for low values of $\Delta T$, the effect is only due to stronger barotropic instability. In order to determine the localization of the CLVs we compare the meridionally averaged variance of the CLVs during blocked and unblocked phases. We find that on average the variance of the CLVs is clustered around the center of blocking. These results show that the blocked flow affects all time scales and processes described by the CLVs.

References

Critical Transitions and Perturbation Growth Directions

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Abrupt drastic shifts, called critical transitions, have been reported in a variety of systems. Seizures in epileptic patients, sudden crashes in financial markets and abrupt changes in the climate and in ecosystems are all examples of critical transitions. A common model for systems exhibiting CTs are fast slow systems [1]. We study critical transitions in several different models of fast slow systems, such as the FitzHugh-Nagumo oscillator [2], a network of coupled FitzHugh-Nagumo oscillators, a model describing Josephson junctions [3] and the Hindmarsh-Rose model [4]. Understanding a system exhibiting critical transitions as a dynamical system close to a bifurcation point, we can expect a critical transition to be preceded by early-warning signs [5, 6]. We investigate changes in the dynamical properties of different dynamical systems before a critical transition occurs. We employ covariant Lyapunov vectors [7-10] to explore the dynamical structure of our models. Namely we use the changes in the direction and the finite time growth rate of the covariant Lyapunov vectors as precursors of critical transitions. Apart from possible practical implementations, such as predictions, we use the relation between predictor and event in order to understand the dynamical origins of the critical transitions. We show that tangencies between the covariant Lyapunov vectors prior to and during transitions is a generic feature of all studied fast-slow models and we argue that the observed tangencies are a manifestation of the well known phenomenon of critical slowing down [11].

References

Alignment of Lyapunov Vectors: A Quantitative Criterion to Predict Large Events?

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The prediction of catastrophic events is arguably one of the most important open problems in physics and in the natural sciences. The great challenge is, of course, to anticipate the duration of the random quiescent intervals and thus to predict impinging undesirable events such as earthquakes, tsunamis, rogue waves, market crashes, political crisis, etc. In this work \cite{1} we argue that the alignment of Lyapunov vectors provides a quantitative criterion to predict the imminence of large-amplitude events in chaotic time-series of observables generated by sets of ordinary differential equations. Explicit predictions are reported for a Rössler oscillator and for a semiconductor laser with optoelectronic feedback.

References

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Fluctuations of Lyapunov Exponents in Extended Chaotic Systems

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Finite-time Lyapunov exponents of generic chaotic dynamical systems fluctuate in time. These fluctuations are due to the different degree of stability across the accessible phase-space. An earlier numerical study [1] revealed that the diffusion coefficient \( D \) of the Lyapunov exponents (LEs) exhibits a non-trivial scaling behavior, \( D(L) \sim L^{-\gamma} \), with the system size \( L \). For chaotic dissipative systems, we show that the wandering exponent \( \gamma \) can be expressed in terms of the kinetic roughening exponents associated with the corresponding Covariant Lyapunov Vector (CLV) surface (defined through a logarithmic transform) via the universal scaling relation \( \gamma = z - 2\alpha \). Our theoretical predictions are supported by the numerical analysis of several spatially-extended systems [2]. In particular, we find that the wandering exponent of the first LE is universal: in view of the known relationship with the Kardar-Parisi-Zhang (KPZ) equation, \( \gamma \) can be expressed in terms of known critical exponents. Furthermore, our simulations reveal that the bulk of the spectrum exhibits a clearly different behavior and suggest that it belongs to a possibly unique universality class, which has, however, yet to be identified. In all cases, the fluctuation exponent \( \gamma_n \) of the \( n \)-th LE is connected to the \( n \)-th CLV surface via \( \gamma_n = z_n - 2\alpha_n \), in agreement with our theory. In contrast, in generic Hamiltonian lattices the diffusion coefficient of the maximum Lyapunov exponent diverges in the thermodynamic limit [3]. We trace the divergence back to the long-range correlations associated with the evolution of the hydrodynamic modes. In the case of normal heat transport, the divergence is even stronger, leading to the breakdown of the usual single-function Family-Vicsek scaling ansatz. A similar scenario is expected to arise in the evolution of rough interfaces in the presence of a suitably correlated background noise.

References

Dynamical Network Control and Applications to Power Grids (MS7)

Organizers: Simona Olmi, Eckehard Schöll, Anna Zakharova

A State Space Topology of Sustainable Management and its Implications for Power Grids

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To keep a dynamical system permanently in a desirable region of its state space, one needs to understand not only the quantitative internal dynamics of the system and the available options for influencing it (management or control) but also the structure of the system’s state space with regard to certain qualitative differences. Important questions are, which state space regions can be reached from which others with or without leaving the desirable region, which regions are in a variety of senses ”safe” to stay in when management options might break away, and which qualitative decision problems may occur as a consequence of this topological structure?

In this talk, I present a mathematical theory of the qualitative topology of the state space of a dynamical system with management options and desirable states, as a complement to the existing literature on optimal control. I suggest a certain terminology for the various resulting regions of the state space and perform a detailed formal classification of the possible states with respect to the possibility of avoiding or leaving the undesired region. Our results indicate that, before performing some form of quantitative optimization such as a cost minimization, a sustainable and resilient management may require decisions of a more discrete type that come in the form of several dilemmas, e.g. choosing between eventual safety and uninterrupted desirability, or between uninterrupted safety and larger flexibility.

I illustrate the concepts and dilemmas drawing on conceptual models from climate science, ecology, coevolutionary Earth system modeling, economics, and classical mechanics, and discuss their potential relevance for the management of power grids, in particular suggesting several nested safety levels.

References

Power Grids and Turbulence – On the Stability and Quality of Power Grids Subjected to Intermittent Feed-in

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Feed-in fluctuations induced by renewables are one of the key challenges to the stability and quality of electrical power grids. In particular short-term fluctuations disturb the system on a time scale, on which load balancing does not operate yet and the system is intrinsically governed by self-organized synchronization. Due to the turbulent nature of the generation process, especially the feed-in fluctuations from wind power are strongly non-Gaussian with intermittent increment statistics. We investigate the impact of short-term wind fluctuations on the basis of a Kuramoto-like power grid model considering stability in terms of desynchronization and frequency and voltage quality aspects. We compare intermittent feed-in with a realistic power spectrum, correlated Gaussian noise of the same spectrum, and Gaussian white noise. We found out that the likelihood of severe outages is mainly determined by the temporal correlation of the feed-in. The intermittent nature of wind power is transferred into frequency and voltage fluctuations. This establishes a novel type of fluctuations with severe consequences on frequency and voltage quality, which are beyond engineering status of knowledge.
A Statistical Approach for Resilience Analysis of ESS Deployment in Power Systems with High RES Penetration

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The increasing impact of Renewable Energy Sources (RES) on modern power grids is pointing out the need of models capable to forecast and assess the impact of their fluctuating power output. Given the complexity of power systems, these models should be able to capture both their physical and the economic features. In particular, it is becoming more and more necessary to identify the relation between market-based frequency control and physical system resilience. This is strongly related to the identification of the overall system limits, and to the proposal of solutions that allow to overcome them.

In this talk, a new stochastic model able to measure the system resilience in presence of RES and load fluctuations is proposed. This model is based on the ensemble approach, evaluated on the base of a numerical sampling. By means of this approach, it has been possible to identify probabilistic measures associated to the system resilience, regarding the system available resources and the lines congestions.

These measures have then been used for assessing the impact of the market-based frequency control in the Italian Transmission system, in presence of RES and loads fluctuations. Moreover, the proposed model has been used for studying the impact of the presence of Energy Storage Systems (ESS) on the same system, comparing the impact of localized, distributed and mixed storage strategies. As a result, it will be shown how distributed storage systems lead to a better system resilience in the studied grid.
Network Robustness and the Impact of Transmission Line Failures

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The robust operation of physical distribution and supply networks is fundamental for economy, industry, and our daily life. For instance, a reliable supply of electric power fundamentally underlies the function of most of our technical infrastructure. In periods of high loads, the breakdown of a single element of the power grid can cause a global cascade of failures implying large-scale outages with potentially catastrophic consequences.

In this talk I will review the theory of transmission line outages and the robustness of networks. Once a line in the network fails, the flow must be rerouted over alternative pathways. To assess the robustness of a network we must understand where flows are rerouted and quantify how much capacity is available for this task. I will discuss the mathematical formulation of the problem, present some recent results, and demonstrate some illuminating connections to other fields of theoretical physics and applied math.
From Conventional to Renewable Power: Insights on the Role of Grid Heterogeneities and Long-range Connectivity

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The influence of heterogeneities characterizing transmission lines and generators on the functioning of power grids is investigated, focusing on the situation where conventional power plants are replaced by renewable power sources. Two problems are addressed.

First, we study the probability of single line failure, showing that it is necessary to consider the maximum power at the generators where renewable power is injected into the grid. In the case one single renewable source is considered, a simple formula for outage probability can be derived which also incorporates the mean injected power and operating time scales of human intervention. Our derivation is based on empirical sets taken at the North Sea. In the case of two or more renewable sources, we show some unexpected behavior relating the distance between sources and the outage line.

Second, we report on simulations of the time-dependent power flow in grids, where power input from a fraction of the generator nodes is fluctuating and follows stochastic dynamics mimicking statistical features of wind and solar power injection. Different measures of the grid stability are discussed, as, for example, frequency stability and phase synchronization.
Josephson Junctions as a Prototype for Synchronization of Nonlinear Oscillators: from Huygens Clocks to the Utility Power Grid

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Josephson junctions are nonlinear oscillators that, for practical purposes, should be synchronized. Synchronization of coupled Josephson junctions can be described by a general model for nonlinear coupled oscillators, the Kuramoto model. There are, therefore, also other systems of coupled oscillators that are related to Josephson junctions, from the Huygens study of clocks mounted on a common support to bridge oscillations. About ten years ago it emerged an unexpected link of Josephson junctions to the utility grid for transmission of electrical power. Most importantly, the instability occurring in a simple machine-generator system is mathematically equivalent to the loss of stability of the Josephson junction. Specifically, the loss of stability of the power-grid is equivalent to the switch from the Josephson supercurrent to the McCumber rotating solution. It is thus possible to relate the synchronization problems typical of Josephson superconducting electronics with the stability problems of the utility power grid.
Dynamics of Decentrally Controlled Power Grids

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The ongoing energy transition results in more decentralized, distributed generation and higher loads on existing transmission lines. Current as well as future smart grid control mechanisms aim to keep the grid stable and are often centralized and based on steady state behavior thereby neglecting the dynamical nature of power grids. Here we present the concept of Decentral Smart Grid Control, where the electricity price is directly linked to the local grid frequency at each customer or producer. The central idea is that the grid frequency provides all necessary information about the current power balance such that it is sufficient to match supply and demand without the need for a centralized IT infrastructure. We analyze its dynamical stability for simple motif networks. An extended dynamical analysis is important to understand and prevent cascading failures in power grids.

References

A Mathematical Model for Energy Distribution in Urban Areas

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The intense urbanization and the remarkable energy consumption deriving from urban areas are responsible for more than the 67% of the world’s energy demand (IEA, 2008) and produce more than the 70% of the global CO2 emissions (IPCC, 2013). In this context, the traditional configuration of the energy distribution is progressively changing due to the diffusion of autonomous energy production systems, i.e., systems with renewable energy resources directly exchanging energy with private connections among geographically neighboring users. In this paper, a mathematical model based on complex networks is proposed to analyze how the private energy exchanges impact the energy distribution in an urban area. To the purpose, the urban area is sorted into connected territorial units characterized by an energy demand and a potential energy production. The model calculates the energy flow distribution in the network. An index is then introduced to measure the efficiency of the network. The procedure is tested for different scenarios, including the random positioning of node with renewable energy production and their correlation with social effects. Results show that the presence of correlations in the position of the autonomous energy production systems may significantly reduce the positive effects of their introduction, while increasing the connections generally leads to an improved urban energy distribution network.

References

Towards the Impact of Structural Perturbations in Power-grids: the Role of Algebraic Constraints

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A central question in many complex networks is the following: What is the impact of structural perturbations such as the addition of a link on the stability of certain states? In the case of diffusive dynamics governed by ODEs, many answers have been found to questions of this type in the last decades. However, it is known that some models of power-grids involve algebraic constraints. These constraints can lead to counter-intuitive effects such as the Braess paradoxon, as was recently shown. Technically, we are concerned with a set of so-called Differential-Algebraic Equations (DAEs). Although basic stability results for this class of equations are similar to the ODE case, the spectral analysis for DAEs is more involved. More precisely, the stability is determined by the solutions of a generalized eigenvalue problem

$$\det \left[ \lambda^2 L_1 + \lambda L_2 + \lambda \right] = 0,$$

where the $L_i$ are grounded Laplacian matrices. Here, we investigate the stability in electrical circuits which may act as a simplified model for power-grids. We present first results regarding the impact on stability of adding links to the network.
Solitary States in the Kuramoto Model with Inertia

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Solitary states represent a new phenomenon in networks of identical oscillators, when a single or a few oscillators detach spontaneously from the synchronized cluster and start to behave differently, e.g., rotate with another frequency. Mathematically, this is spatial chaos as the number of the states (attractors) grows exponentially with the network size $N$. Solitary states are different from the chimera states, where the oscillators split usually into two well defined and self-organized groups, synchronized and desynchronized. In the talk, the solitary state appearance is reported for the network of $N$ Kuramoto oscillators with inertia, which is commonly used as a model for power grids. It is found that this kind of behavior is typical for all types of coupling (local, non-local, and global) as well as for different network sizes ranging from $N = 3$ up to infinity. Solitary states arise in a homoclinic bifurcation on a 2D manifold with increase of the phase lag $\alpha$ or the coupling strength $\mu$, and they exist further in a huge region of the parameter space.

References

Modeling of a Complex Biochemical System for Various Applications

Ljiljana Kolar-Anić\textsuperscript{1,2}, Željko Ćupić\textsuperscript{2}, Vladimir M. Marković\textsuperscript{1}, Ana Stanojević\textsuperscript{1}, Stevan Mačešić\textsuperscript{1}, and Vladana Vukojević\textsuperscript{3}

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In general, biochemical systems are very complex and mutually intertwined, so it is difficult to define one of them to be examined separately. However, we usually need to analyze dynamic states of a certain subsystem or one specific species, only. In order to condense global knowledge about the system, the core model must be defined. Then, if it is well-defined, the model can be easily upgraded for different aims. For that purpose, the stoichiometric approach to modeling has numerous advantages: it is consistent with known biochemical data, model predictions can be more directly compared with real experiments, and the model can be more easily expanded to account for additional species and their interactions that modulate the main process.

To illustrate the whole problem and demonstrate the validity of the stoichiometric approach for describing complex nonlinear biochemical systems, we shall consider a low-dimensional model of the hypothalamic-pituitary-adrenal (HPA) axis. This model possesses highly dynamical structure that integrates and controls the functions of the nervous and endocrine systems under normal physiological conditions and stress [1-3]. We show that the model can be easily expanded to account for additional reactions and additional species, such as internal and external cholesterol, which is the only precursor of steroid hormones [4] and, also, ethanol, which in this model play the role of a typical external species. Both cholesterol and ethanol can modulate the HPA axis dynamics, either separately or together.

References

Influence of Circadian Function on the Dynamical States and Bifurcation Diagrams of the Hypothalamic Pituitary-adrenal Axis

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Dynamic properties of a hypothalamic pituitary-adrenal (HPA) axis were described by nonlinear five-dimensional stoichiometric model. [1-7] The complex interaction between ultradian and circadian oscillations is the subject of the present work. For this purpose, the qualitative transitions between dynamic states was investigated as a function of rate constants of every reaction step. Bifurcation diagrams were constructed and both, supercritical Andronov-Hopf and saddle loop bifurcations were identified.

It was found that the basal (healthy) physiological conditions of HPA axis are close to an Andronov-Hopf bifurcation. Modeling suggests that the proximity to a supercritical Andronov-Hopf bifurcation can give the HPA axis two important properties. One is the flexibility to respond to external stimuli and the other is ability to return to the original dynamic state afterwards, which is essential for maintaining homeostasis. Adaptation to daily cycles is one example of this extraordinary property of the HPA axis.

References

Modeling Hypothalamic-pituitary-adrenal Axis Dynamics under Various Forms of Externally and Internally Induced Cholesterol Perturbations

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Specific oscillatory dynamics of a neuroendocrine hypothalamic-pituitary-adrenal (HPA) system has proven to be necessary for maintaining regular basal physiology and formulating appropriate stress response to various types of external and internal stressors [1]. Cholesterol, being a precursor of all steroid HPA axis hormones, can cause significant alterations of the HPA axis dynamics [2]. In order to examine its particular influence on the HPA axis dynamical behavior, we employ stoichiometric modeling of HPA axis activity [2-4], and simulate various forms of cholesterol perturbations, such as instantaneous pulse perturbations, finite duration pulses with an asymmetrically distributed concentration profile, and kinetically controlled chronic modulations of cholesterol levels. Results of our numerical simulations show there is a complex, nonlinear dependence between the HPA axis responsiveness and different types of cholesterol concentration perturbations, indicating to the importance of kinetic modeling and dynamical systems theory [4] for more comprehensive mechanistic insights into large-scale self-regulatory and homeostatic processes governing this neuroendocrine system.

References

From Phenyl Acetylene to Mono- and Di-alkyne-terminated Poly(Ethylene Glycol) as Substrates in Oscillatory Carbonylation Reactions

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Carbonylation reactions are a direct route to synthesize carbonyl compounds [1]. The palladium-catalyzed oxidative carbonylation of phenylacetylene gives rise to a number of products depending on the conditions [2] and attracts particular attention following the discovery of its oscillatory nature [3,4]. Recently, Donlon and Novakovic demonstrated that functional polymers can also act as substrates in oscillatory chemical reactions [5]. Both experimentally and in a modelling study, they showed that oscillatory pH behavior can be reproducibly achieved via palladium-catalysed carbonylation of mono-alkyne-terminated poly(ethylene glycol) (PEGA). The discovery of a polymeric substrate oscillatory chemical system has opened new avenues that could lead to the transition from oscillatory chemistry taking place in solution to oscillations in polymeric materials of various structures. One example of such materials are hydrogels responsive to a change in pH. In combination, the chemical oscillator has the potential to drive conformational change in the responsive hydrogel autonomously, independently of its environment. This development could lead to applications such as rhythmic drug delivery or mechanoresponsive cell proliferations. In this work, further studies of oscillatory behavior using alkyne-terminated poly(ethylene glycol) are reported. In addition, reproducible oscillations with a novel dynamic were captured when di-alkyne-terminated poly(ethylene glycol) (PEGDA) was used showing that poly-functional polymeric substrates are also viable in oscillatory systems and have new features to offer.

References

Pattern Formation in the H$_2$O$_2$-based Chemical Oscillators, Caused by Inhomogeneous Temperature Field

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Typical spatiotemporal and spatial patterns reported for aqueous media emerge due to the coupling of nonlinear chemical kinetics with the diffusion of reacting particles, with eventual contribution from excitable characteristics. Moreover, such phenomena are usually explained assuming isothermal conditions.

In our searches of new spatiotemporal instabilities in aqueous media we studied several chemical systems in which hydrogen peroxide was an oxidant for various sulfur-containing species [1, 2]. In one of these systems, containing hydrogen peroxide and thiocyanates as the main reactants [1], we discovered, in the thin layer batch reactor, the emergence of luminescent patterns (Fig. 1) which could not be explained in terms of the assumption of homogeneous temperature distribution. Based on experimental studies and numerical modeling of the reaction kinetics, we were further able to prove that the observed patterns were essentially the phase waves, caused by the inhomogeneous distribution of solution temperature which affected the local frequency of oscillations [3].

Also in another chemical system, containing hydrogen peroxide and thiosulfates as the main reactants [2], the patterns could be observed only in the presence of externally imposed temperature gradient. In this case the color pH front (visualized by thymol blue indicator), progressing along the quasionedimensional reactor was reported (Fig. 2 left) [4]. The mechanistic reason for the observed instability is again the dependence of the chemical reaction kinetics on temperature, i.e. the thermokinetic coupling. Also in this case the experimental findings were successfully reproduced by numerical modeling (Fig. 2 right) [4].

We consider these phenomena a manifestation of novel and rather unique examples of instabilities of thermokinetic origin in liquid media.

References

Method for Determination of Mechanisms Responsible for Complex Dynamics in the Model of Bray-Liebhafsky Reaction

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Oscillating chemical systems are well known for displaying complex behavior under different experimental conditions [1,2]. Main characteristic of these systems is their ability to exhibit diverse dynamics such as: simple oscillations, mixed-mode oscillations, intermittent oscillations and chaos [36]. Bray-Liebhafsky (BL) reaction is example of oscillating chemical systems capable to display complex types of dynamics. Modeling of the complex dynamics in the model of BL reaction is very serious problem due to the fact that it can be located only in very narrow range of control parameters which complicates finding mechanistic explanations. Thus, in this paper we present a method based on stoichiometric network analysis (SNA) [7,8], which allows detection of minimal sub-models in the model of BL reaction whose mutual interaction results in complex types of dynamics such as mixed-mode oscillations.

References

The Application of Stopped-flow Technique for Investigation of Reaction Dynamics of Iodine Oxidation with Hydrogen Peroxide

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The oxidation of iodine to iodate with hydrogen peroxide is one of the two periodically dominating processes of the Bray-Liebhafsky (BL) oscillatory reaction [1, 2]. Although, another one, the reduction of iodate to iodine, is relatively well examined process, for which was shown to have kinetics closely related to Dushman reaction, oxidation of iodine has not been investigated enough [3, 4]. Therefore, the study of the iodine oxidation can contribute to a better understanding of the BL reaction as well as other oscillatory reactions with iodine species.

Determination of iodate amount originating from iodine oxidation is one of the ways for studying mechanism of this reaction. It has shown that stopped-flow technique may be successfully utilized for iodate determination in the presence of hydrogen peroxide by titration with excess of iodide [5]. With the aim to investigate kinetics of iodine oxidation with hydrogen peroxide, the amount of produced iodate is measured by stopped-flow titration in different reaction points, where reaction conditions were similar to one presented in [5]. It is found that rate of iodine conversion to iodate is generally decreasing during the reaction. In the other words significant amount of iodate is produced in the first few minutes, while the conversion of the rest of the iodine takes up to two hours. Also, results show that, at considered conditions, almost all iodine ends up as iodate.

References

Robust and Detailed Kinetic Model of the Chlorite-thiosulfate Reaction

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Fascinating nonlinear dynamical features of the chlorite-thiosulfate reaction has long been discovered. The title reaction is autocatalytic with respect to hydrogen ion [1], in unbuffered media it behaves as an irregular clock reaction [2]. Moreover, it displays complex periodic and aperiodic oscillations [3] and chaos [4] in a continuously fed tank reactor. Even though these characteristics are known for decades, no detailed mechanism has yet been established to explain these phenomena. The intermediates, like hypochlorous acid, tetrathionate ion and chlorine dioxide make this reaction extremely complicated since they are capable of reacting not only with the reactants but also with each other combining a complex network. During the last twenty years our research group stepwisely elaborated the kinetic models of the subsystems of the parent reactions. Among them those of the thiosulfate-chlorine dioxide [5,6], hypochlorous acid-chlorite [7,8], tetrathionate-hypochlorous acid [9], thiosulfate-hypochlorous acid [10] and tetrathionate-chlorite [11] reactions have been systematically established. Having these information in hand, now we present a robust kinetic model that is able to describe the most important kinetic features of the chlorite-thiosulfate reaction preserving the perfect description of its subsystems as well.

References
Emergence of Chemical Oscillations from Nanosized Target Patterns

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Non-linear dynamics are observed in a variety of reactive systems such as the surface of nanoparticles of catalysts. Probing the reactions and their dynamics at the scale of a single nanoparticle remains challenging, due to the scarcity of high-resolution techniques. The nanoscale resolution of the field emission microscopy (FEM) allows studying the dynamics of catalytic reactions taking place at the surface of a nanosized metal tip. With this technique, the dynamics can be probed in real-time and during the ongoing reactive processes. The microscope is run as an open reactor so that the system is kept far from its thermodynamic equilibrium. Under these conditions, chemical reactions can induce time and space symmetry breaking of the composition of a system.

This study reports on the observation and analysis of the emergence of periodic oscillations during the catalytic hydrogenation of NO\textsubscript{2} on a single nanoparticle of Pt. By exploiting the nanoscale resolution capabilities of FEM, the reaction can be probed down to 10 nm\textsuperscript{2}. By changing a control parameter, it is possible to observe different behaviors and to determine the type of bifurcation leading to self-sustained periodic oscillations. The robustness of these oscillations is quantified via temporal autocorrelation functions and dynamical attractor reconstruction. High-speed experiments highlight the presence of diffusing processes down to the nanoscale between active facets, proving that the consecutive ignition of the active facets is due to a coupling via surface diffusion. The propagation of chemical waves on a single facet of the nanocrystal is also observed. These waves take the form of target patterns, which are observed for the first time at the nanoscale \cite{1}. The velocity of the observed waves is of the order of a few µm/s, which is in good agreement with previous studies of catalytic reactions at larger scales.

Field emission microscopy is a powerful technique allowing for a better understanding of catalytic systems at the molecular level. The experiments prove the robustness of dissipative, nonlinear behaviors down to the nanoscale, without a significant loss of correlation due to fluctuations inherent to small chemical systems. These results shed a new light on the conditions under which collective order can emerge at the nanoscale.

References

Assessment of Dynamics of the Oscillating Reactions with Chiral Compounds

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An ultimate goal in studying non-linear and oscillating reactions is investigation of the kinetics of such processes with adequate analytical techniques. In this talk, performance and limitations of several analytical techniques are going to be discussed and the examples are going to be given upon a novel class of the oscillating reactions, i.e., the oscillating chiral conversion and the oscillating peptidization of α-amino acids. Several features characterize an adequate analytical technique, and the most important ones are selectivity, precision, sensitivity and a possibility to work in continuous registration mode, when quantifying non-linear concentration changes going on in a reaction system. In this context, performance and limitations of the following analytical techniques will be discussed:

- the chiral high-performance liquid chromatography with the evaporative light-scattering detection (HPLC-ELSD);
- the non-chiral HPLC-ELSD;
- polarimetry (in continuous registration mode);
- turbidimetry (in continuous registration mode).

As each aforementioned analytical technique has its intrinsic limitations, the applicability scope of some auxiliary techniques will also be discussed, which allow to circumvent certain drawbacks of these principal techniques. The main auxiliary techniques discussed in our talk and the gain obtained with their aid will be:

- liquid chromatography with mass spectrometric detection (LC-MS);
- scanning electron microscopy (SEM);
- spectroscopy of chiral dichroism (CD) in the far UV range.

Finally, conclusions will be drawn as to the further need for more robust and better performing analytical techniques, able to help discover new classes of non-linear and oscillating reactions, and to provide better characteristics of those already discovered.
Fluid Dynamics Simulation Tools: Softwares Through the Eye of the Physicist (MS9)

Organizer: Izabella Benczik

A User Friendly Climate Model: The Planet Simulator

Mátýás Herein

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As the complexity of general circulation models has been and still is growing considerably on their way to Earth system models, it is not surprising that, for both education and research, models simpler than those comprehensive models at the cutting edge of the development, are becoming more and more attractive: They run fast and can be used to simulate millennia and longer timespans in relatively short real time. They can use inexpensive hardware like workstations with no need to buy time on mainframes. These medium complexity models do not simply enhance the climate model hierarchy. They support understanding atmospheric or climate phenomena by simplifying the system gradually to reveal the key mechanisms. We present here such a model of intermediate complexity, which was developed at the University Hamburg, for the university environment: the Planet Simulator. It can be used for education, training the next GCM developers, to support scientists to understand climate processes, and to do fundamental research, as well.

References

The Dynamics and its Parameter Dependence of Radiative-convective Equilibrium in ECHAM6.3

Gábor Drótos

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The climate and its sensitivity is explored in a global model run in radiative-convective equilibrium: results are presented from simulations with the ECHAM6.3 atmospheric model of the Max Planck Institute for Meteorology, coupled to a slab ocean. Simulations both with and without a parameterised representation of deep convection are conducted for CO2 concentrations ranging from one eighth of present day values to thirty-two times the present day, and for variations in the solar constant of more than a factor of two. Very long simulations, in some cases more than a thousand years, are performed to adequately sample the attractor of the different climate states of the model. The linearized sensitivity itself of the system exhibits strong dependence on all of the factors varied. This results from the appearance of different dynamical regimes giving rise to nontrivial changes in the cloudiness.

References
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Dynamics of Hepatitis C Virus Replication in Single Liver Cells: Full 3D (Surface) PDE Modeling with UG4

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Advanced simulations within biophysical applications ask for advanced algorithms and implementations which are running efficiently on massively parallel high performance computers. The software framework UG4 (“unstructured grids”) fulfills these preconditions. I will discuss a model of Hepatitis C virus replication inside single liver cells: the experimental basics, the modeling and simulation details, and the biophysical meaning of the estimation of the diffusion constant of a major player in the replication of the genetic information of the Hepatitis C virus (HCV), namely the NS5A viral protein. NS5A motion is restricted to the surface of the Endoplasmatic Reticulum (ER, a medusa-hair like important cell compartment). Hence, the dynamics of NS5A are described by surface PDEs (sPDE) which mimic experimental FRAP (fluorescence recovery after photo-bleaching) time series data. This enabled us to derive accurate values for the diffusion constant of NS5A on the ER surface. The estimated diffusion-constant values are intended to enter spatio-temporal resolved models of HCV replication dynamics at a cellular level. The sPDE computations were performed with UG4 upon large unstructured grids representing realistic reconstructed ER surfaces. We use Finite Volume discretization and massively parallel multigrid solvers as implemented within UG4 to solve the arising sPDEs. The basic structure of the UG4 LGPL open source software framework are discussed. I explain the context of the application for the parameter estimations. It required a substantial amount of single sPDE evaluations which we performed on the HLRS Stuttgart Hermit and Hornet supercomputers for various experimental data sets and for various geometric setups.

In the outlook of the talk I point out how UG4 can be applied to various related fields, in particular in fluid dynamics and continuum mechanics.

References

Nonlinear Delay Equations (MS10)

Organizer: Gergely Röst

Smoothness Problems for Differential Equations with State-dependent Delay

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For differential equations with state-dependent delays a satisfactory theory is developed by H.-O. Walther on the so called solution manifold to guarantee $C^1$-smoothness for the solution operators. We present examples showing that better than $C^1$-smoothness cannot be expected in general for the solution manifold and for local stable manifolds at stationary points on the solution manifold. Then we propose a new approach to overcome the difficulties caused by the lack of smoothness. The mollification technique is used to approximate the nonsmooth evaluation map with smooth maps. Several examples show that the mollified systems can have nicer smoothness properties than the original equation. Examples are also given where better smoothness than $C^1$ can be obtained on the solution manifold.
Geometric Methods for Global Attraction in Systems of Delay Differential Equations

Alfonso Ruíz-Herrera

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In this talk we deduce new criteria of global attraction in systems of delay differential equations. Our methodology consists in "dominating" the nonlinear terms of the system by a scalar function and then studying some dynamical properties of that function. One of the crucial benefits of our approach is that we obtain sharp delay-dependent criteria of global attraction. We apply our results in a gene regulatory model and the classical Nicholson’s blowfly equation with patch structure.
A Discrete Delay Epidemic Model for Isolations

Stefan Ruschel

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Infectious diseases are among the most prominent threats to mankind. When an outbreak is not foreseen, preventive healthcare cannot be provided immediately. In this case, the unanimous means of disease control is the isolation of infected individuals. As a model, we propose a system of Delay Differential Equations and offer our analysis based on the geometric theory of semi-flows. We provide upper bounds for the time of diagnosis and isolation, such that this strategy is effective.

Acknowledgment

This is joint work with Serhiy Yanchuk (TU Berlin), Tiago Pereira (Universidade Sao Paulo) and Lai-Sang Young (New York University).
Morse Decomposition for Scalar Delay Difference Equations

Ábel Garab
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Consider the following class of difference equations

\[ x_{k+1} = f(x_k, x_{k-d}), \]

where \( f : \mathbb{R}^2 \to \mathbb{R} \) is a \( C^1 \) function, which is strictly increasing in its first variable and fulfills either \( yf(0,y) > 0 \) or \( yf(0,y) < 0 \) for all \( y \in \mathbb{R} \setminus \{0\} \). Under the assumption that the global attractor exists, we give a Morse decomposition of the attractor. The decomposition is based on an integer valued Lyapunov function introduced by Mallet-Paret and Sell [1] as a discrete time counterpart of their celebrated discrete Lyapunov function for delay differential equations. This is a joint work with Christian Potzsche (Alpen-Adria Universität Klagenfurt).

References

A Space-time Finite Element Method for Neural Field Equations with Transmission Delays

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Neural field equations are models that describe the spatio-temporal evolution of (spatially) coarse grained variables such as synaptic or firing rate activity in populations of neurons. We consider a single population of neurons, distributed over some bounded, connected, open region, whose state is described by their membrane potential. These potentials are assumed to evolve according to the integro-differential equation with space dependent delay

$$\frac{\partial}{\partial t} u(t,x) = -\alpha u(t,x) + \int_{\Omega} J(x,r) S(u(t - \tau(x,r),r))dr, \quad \alpha > 0.$$  

Neural field models with transmission delay may be cast as abstract delay differential equations [4], which is the starting formulation for our numerical discretization. The numerical treatment of these systems is rare in the literature and has several restrictions on the space domain and the functions involved, [1, 2]. The aim of this work is the development of an accurate numerical method without introducing limitations to its applicability. We present and analyze a novel time-discontinuous Galerkin finite element method, which is well established to solve partial differential equations, [3]. We give a theoretical analysis of the stability and order of accuracy of the numerical discretization and demonstrate the time-discontinuous Galerkin method on a number of neural field computations.

References

Self-organization, Self-propulsion, Compartmentalization and Their Applications (MS11)

Organizer: István L. Lagzi

Characteristic Motion of a Self-organized Object Based on Nonlinearity

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We have investigated simple self-propelled objects which indicate characteristic features of motion depending on the physicochemical environments [1] The driving force of motion is the difference in the surface tension around the object. Nonlinear phenomena, such as oscillation, bifurcation, and synchronization, were reproduced as the characteristic features of motion based on reaction-diffusion kinetics. I would like to talk about (i) mode-bifurcation between oscillatory motion and continuous motion in couple with chemical reactions, (ii) reciprocating motion depending on the chemical property of surfactant molecule on water, (iii) memory motion depending on the trajectory of motion. I would like to discuss the relationship between these characteristic motion and physicochemical nonlinearity.

References

Compartmentalization as a Prerequisite for the Origin of Life

Ádám Kun

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The appearance of molecular replicators (molecules that can be copied) was probably a critical step in the origin of life at the early stages of the RNA world [1]. However, error prone replication results in sequences that are not useful, but can be replicated faster than the ribozymes. Thus parasites form. They take over a well-mixed system, and would have prevented life from taking off, unless the replicators were compartmentalized in reproducing ribocells. Compartmentalization in itself does not solve all problems of the coexistence of replicators, and creates some of its own. Chief among them are the random division of cells, which can lead to loss of information [2]. Furthermore, nearly a hundred genes seem to be required for a minimal ribocell to function. How could such a system evolve considering that control of ribocell reproduction would seem to require a host of evolved replicators? We show here that a simpler population structure, based on cycles of transient compartmentalization and mixing of RNA replicators, is sufficient to prevent takeover by parasitic mutants [3]. Transient compartmentalization tends to select for ensembles of replicators that replicate at a similar rate, including a diversity of parasites that could serve as a source of opportunistic functionality. Thus transient compartmentalization could have allowed life to take hold.

References

Nonlinear Behavior of a Self-propelled Droplet Coupling with the Belousov-Zhabotinsky Reaction

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Spontaneous droplet motion has been theoretically predicted as an instability of homogeneous distribution of surfactant on the droplet interface \cite{1,2}, and has been demonstrated in real experimental systems such as an oil droplet in water \cite{3} or an aqueous droplet in oil \cite{4}. These droplets are propelled by an interfacial chemical reaction of surfactant which induces Marangoni flow on an oil/water interface. So, the droplet motion strongly depends on the rate of the chemical reaction. Here, in order to mimic nonlinear behaviors observed in biological systems such as periodic oscillation, hysteresis, and bifurcation, we attempted to introduce a nonlinear chemical reaction into a self-propelled aqueous droplet. Nonlinear chemical reaction is one of the succeeded biomimetic systems that reproduce characteristics observed in biological systems. The Belousov-Zhabotinsky (BZ) reaction is one of the typical nonlinear reactions and shows oscillation of intermediates concentration, i.e., oxidized catalyst, bromine, and so on. Therefore, if the concentration of intermediates affects to the driving force of droplet motion, the droplet might show nonlinear behavior reflecting the characteristics of the BZ reaction. It has been known that a bromine aqueous droplet spontaneously moves in monoolein squalane solution \cite{4}. Therefore, the BZ droplet is also expected to move spontaneously because of the intermediate, bromine, and its motion will couple to the BZ reaction. We prepared a BZ aqueous droplet in oil phase with surfactant. Squalane and monoolein was used here as an oil phase and surfactant. When the BZ reaction was reduced or oxidized steady state, the droplet showed continuous motion with constant speed, where the oxidized droplet was faster than the reduced one. On the other hand, the BZ droplet in oscillatory state showed oscillation of speed of the droplet motion \cite{5}. These nonlinear behaviors can be understood as a coupling the droplet motion to the BZ reaction through the concentration of bromine.

References

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Phototactic Behavior of Micrometer-sized Oil Droplets in Surfactant Solution

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Self-propelled motion of micrometer-sized oil droplets in surfactant solution has drawn much attention as the dynamic behavior in a far-from-equilibrium system. Their motion mode can be controlled by the system components and/or chemical reactions. However, precise control over droplet locomotion by external physical or chemical stimuli still remains a major challenge. Here, to control the locomotion mode of oil droplets, we have prepared gemini cationic surfactants having an azobenzene moiety (Azo) [1]. In the solutions of Azo and \(N\text{-hexadecyl-}\,N\text{-hexadecylammonium bromide (C16TAB)}, \) when the emulsion was entirely irradiated with UV light, oil droplets comprising a benzaldehyde-derivative immediately exhibited negative phototaxis in the opposite direction to the light source. It was confirmed from \(^1\)H-NMR analysis that isomerization of Azo from trans- to cis-isomer readily occurred under UV irradiation. In addition, the interfacial tension between oil and aqueous solution containing Azo increased slightly but instantaneously. Thus the negative phototaxis of the droplets may be explained by the generation of heterogeneity in the interfacial tension of the droplet surface that was induced by the isomerization of Azo. Because oil droplets exhibited the negative phototaxis to multiple UV irradiations from different directions, the emulsion system may be highly effective for applications as transporters and interested in term of the dynamics of far-from-equilibrium system.

References

Patterns Formation in a Pulsating Drop

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Surface tension or buoyancy-driven instabilities are at the origin of shape modifications and motion of drops. They result from the coupling of physico-chemical processes among which evaporation, solubilization, solute transfer, surfactant adsorption/desorption, aggregation and chemical reactions. Desired processes can be selected by the choice of chemicals and experimental conditions [1]. We have observed a remarkable succession of dynamical regimes for dichloromethane (CH\textsubscript{2}Cl\textsubscript{2}, 25 µL) drops setting on aqueous solutions of cetyltrimethylammonium bromide (CTAB) [2]. The surfactant concentration, used as a control parameter, induces an amazing range of shapes and motion patterns. At low surfactant concentration, they are related to spreading and dewetting processes giving rise to directional motion or pulsations. At intermediate concentrations, rotational motion becomes predominant. At the highest concentration, drops have a polygonal rim featuring several small tips. Coupled to these shape-forming processes is the emission of smaller droplets. This system is the first example of such a sequence of highly ordered patterns induced by coupled hydrodynamic instabilities. We will mainly focus on the pulsating regimes observed in the presence of 0.5 mM CTAB in the aqueous phase [3]. The detailed analysis including the drop behavior during the induction period (before pulsations) [4], volume effects and container size was performed. The addition of CTAB also in the drop modifies the observed oscillations: frequency is increased but also the resulting patterns. The drop shows a perfectly circular expanding rim but the most impressive changes are obtained during the receding phase of the film. A flower-like pattern of an amazing regularity is obtained together with the emission of smaller droplets in a mode never observed before. The patterns are related to dynamical features which relevance covers most of the behaviors obtained in any application involving liquid/liquid interfacial processes such as spreading, dewetting, Marangoni-driven motion or drop division. The present system appears as a source of inspiration for further applications in the domain of self-motion and deformation and also in microfluidics in relation with micro-reactor stirring and droplet emission.

References

Giant Vesicles as Host Reactors for Nonlinear Chemical Reactions

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Giant lipid vesicles (GVs) are intensively studied in different areas of biomimetic chemistry, biomembrane physics and in the field of artificial cell synthesis due to their cell mimicking characteristics. GVs and natural cells share physicochemical properties, such as stability, permeability, self-reproduction and the capability to act as hosts of chemical reactions: indeed, giant vesicles can be easily filled with various compounds, even macromolecules, to allow chemical reactions inside \[1,2\]. In this field, one of the most promising applications is the use of liposomes as micro-reactors for nonlinear chemical reactions in order to understand how different compartments communicate with each other and exchange information emitting chemical signals. In this context, interesting results about the encapsulation of the Belousov-Zhabotinsky oscillating reaction in liposomes were recently obtained by means of micro-fluidic techniques \[3\]. The Belousov-Zhabotinsky reaction has also been replaced with the more biologically relevant urea-urease re-action \[4,5\]. This enzyme-catalysed reaction converts urea into ammonia and carbon dioxide, and its typical bell-shaped rate constant can be exploited to generate nonlinear phenomena such as bistability, high steady state, low steady state and oscillations. To obtain oscillations, in particular, theoretical models predict that the substrate (urea, S) and the negative feedback (an acid, H) should be delivered into the reactor at different rates, such as \( k_H > k_S \) \[6\]. Confinement in semipermeable lipid vesicles can thus guarantee a differential diffusion of S and H, so that conditions for oscillations can be met. Here we present an overview of the methods used for the encapsulation of the chemicals into the vesicles and a description of the dynamical features of the confined systems.

References

Directing the Motion of Aspirin Tablets on Curved Air-water Interfaces

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Controlling the assembly of particles at interfaces is important in many applications from materials science to the pharmaceutical industry. Organic crystals such as aspirin are held at the air-water interface as a result of hydrophobic interactions. Earlier we found that complex surface flows arise as a result of long range Marangoni instabilities that propel the crystals and short range capillary interactions that can attract the crystals to each other, depending on their shape and orientation [1]. Such flows have been well investigated in the case of small biological insects such as water walkers, and also exploited in the self-assembly of hydrophobic objects including polystyrene beads and catalytic particles. There is increasing interest in the development of control methods of particles exhibiting motion at interfaces [2-4]. One mechanism involves sculpting the curvature of the air-water interface through the presence of objects. Here we will discuss how the competition between Marangoni flows and capillarity attractions generated by mm-sized aspirin tablets can be tuned through the curvature of the air-water interface. By placing increasingly hydrophobic objects in the path of the tablet, we are able to manipulate the motion and eventually capture the tablet.

References

Wavefront Propagation in Two-dimensional Optical Bistable Device for Maze Exploration

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Natural computing, a novel information processing scheme utilizing dynamics of various natural phenomena, is attracting attentions as an alternative to silicon-based digital computing. Maze exploration is one of popular application of natural computing. For example, Belousov-Zhabotinsky (BZ) oscillatory reaction wave, self-propelling oil droplet, and movement of true slime mold have been reported to solve mazes [1-3]. In this work, we are investigating a two-dimensional thermo-optical bistable device as a system for wavefront propagation, to realize maze exploration.

In this type of devices, optical bistability is realized through positive feedback between heat generated by photoabsorption and change in photoabsorption induced by temperature-dependent optical absorption coefficient. Under irradiation of bias light at an intensity in the bistable (hysteresis) region, the whole area can stay at "off" (low photoabsorption) state without any perturbation. Once the light intensity is increased above the turn-on threshold at one location, the medium is locally triggered to turn on to high photoabsorption state, and the turn-on wavefront expands two-dimensionally due to thermal diffusion in lateral direction. Maze pattern can be easily defined by patterned light irradiation, and exploration can be started by irradiating strong trigger light at the starting point of the maze.

Theoretically, this device can be modeled using a thermal diffusion equation with heat loss at the device boundary and heat source originated from photoabsorption [4-5]. In the photoabsorption term, temperature-dependent optical absorbance is incorporated, resulting in bistability of the device. Using this theoretical model, we have firstly performed a top-view two-dimensional numerical simulation, and demonstrated maze exploration [4]. Next we performed cross-sectional numerical simulation to obtain temperature distribution in the device [5] by the finite element method (FEM) recently, we performed a full three-dimensional (3D) FEM simulation and demonstrated exploration of Steinbock maze [1]. In the simulation, not only extension of wavefront over the whole maze paths, but also the "reduction mode" in which wavefront withdraws from unconnected dead-end paths by reducing irradiated light intensity, has been realized. Such a reduction mode has ever been reported only in the case of maze exploration with true slime mold. [3].

Experimentally, temperature-dependent photoabsorption is realized using a combination of a layer of material with temperature-dependent optical transmission and a black layer which absorbs light almost completely. Here we employ a liquid crystal 4-pentyl-4'-cyanobiphenyl (5CB) for this purpose: below 35 °C, 5CB is in nematic phase with large optical scattering and therefore low optical transmission, and above this temperature it is in isotropic phase which is highly transparent. We have fabricated devices and experimentally demonstrated wavefront propagation. Experimental wavefront velocity was similar to that obtained by the numerical simulation. We also demonstrated exploration of simple maze patterns.

References

Maze Solving Using Self-propelled and Passive Particles at the Liquid-air Interface

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In non-equilibrium conditions, liquid droplets at the liquid-air interface can exhibit tactic motion in the presence of a gradient of thermodynamic variables. These droplets/particles can sense the environmental stimuli and perform more complex tasks such as finding the shortest path in a maze. We provide two examples for maze solving using tactic droplets and passive particles. In the first case the system consists of a small oil droplet containing fatty acid molecules, and the self-propelled motion is powered by the combination of acid/base chemistry and surface tension effects [1]. This droplet moves toward regions of low pH and find the shortest of multiple possible paths in a maze filled with an alkaline solution. Second example shows that the Marangoni flow, which is generated by the pH or temperature gradient can solve the maze problem [2-3]. The pH or temperature gradient changes the protonation rate of fatty acid molecules, which translates into the surface tension gradient at the liquid-air interface. Generated fluid flow can drag water-soluble dye particles at the interface toward regions of low pH/low temperature (exit). Dye particles placed at the entrance of the maze dissolve during this motion thus visualizing and finding the shortest path and all possible paths in a maze in a parallel fashion.

References

Artificial Chemotaxis of Decanol Droplet Groups

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Liquid droplets are very simple objects which become a very popular object in the field called ”active matter”. We have already shown that droplets consisting of pure decanol are able to move in a gradient of salts and hydroxides in a water solution containing sodium decanoate and thereby to mimic the chemotactic behavior of living cells, which in nature perform oriented chemotactic movements towards chemoattractants or run away from chemorepellants [1]. Although the single droplet artificial chemotaxis has been studied in detail (e.g. in various scenarios including chemotactic maze-solving, stimuli-responsive chemotaxis and chemotaxis-driven reactions) [2], the movement of groups consisting of chemotactic droplets has not been analysed yet. The aim of this project is to find any analogy between collective behaviour of groups consisting of chemotactic liquid droplets and living systems. We have studied experimentally the mutual interactions between droplets in absence of salt and also their chemotactic behavior when the chemical salt gradient was established.

References

Snapshot and Pullback Attractors, a Framework for Understanding Nonautonomous Dissipative Dynamics (MS12)

Organizers: Michael Ghil, Tamás Tél

A Mathematical Theory of Climate Sensitivity and What We Learn About It From Pullback Attractors

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The climate system is nonlinear, complex and variable on many scales of time and space. It is typically studied across a hierarchy of models from low-dimensional systems of ordinary differential equations (ODEs) to infinite-dimensional systems of partial and functional differential equations (PDEs and FDEs). The theory of differentiable dynamical systems (DDS) has provided a road map for climbing this hierarchy and for comparing theoretical results with observations.

The climate system is also subject to time-dependent forcing, both natural and anthropogenic, e.g. volcanic eruptions and changing greenhouse gas concentrations. Hence increased attention has been paid recently to applications of the theory of non-autonomous and random dynamical systems (NDS and RDS). This talk will review the road from the classical DDS applications to low-dimensional ODE climate models to current efforts at applying NDS and RDS theory to non-autonomous FDE and stochastic PDE models. A key role in the latter is played by pullback, snapshot and random attractors, and by the parameter sensitivity of the invariant measures they support.

References

Temperature Fluctuations in a Changing Climate: an Ensemble-based Experimental Approach

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There is an ongoing debate in the literature about whether the present global warming is increasing local and global temperature variability. The central methodological issues of this debate relate to the proper treatment of normalized temperature anomalies and trends in the studied time series which may be difficult to separate from time-evolving fluctuations. Here we investigate the nature of connections between external forcing and climate variability conceptually using an ensemble of experimental runs in a laboratory-scale minimal model of mid-latitude atmospheric thermal convection subject to a prescribed continuously decreasing ‘equator-to-pole’ temperature contrast forcing protocol, mimicking climate change. This work provides, to the best of our knowledge, the first results from any laboratory experiment aiming to model the effects of climate change on mid-latitude atmospheric circulation.

The tabletop-size rotating, differentially heated annular wave tank is a widely studied experimental minimal model of the mid-latitude Earth system. It captures the two essential components of large-scale atmospheric circulation: lateral (‘meridional’) temperature difference and rotation. The working fluid is located in the annular cavity between two vertically aligned co-axial cylindrical side walls: the one at the center (simulating the North Pole) is cooled, whereas the rim (representing the equator) is heated with computer-controlled thermostats. The tank is mounted on a turntable and rotates around its axis of symmetry. The adjustable parameters (fluid depth, rotation rate, temperature contrast) are set to yield approximate dynamical similarity to the terrestrial atmosphere in terms of thermal Rossby number and Taylor number.

Despite of the large variability in the ensemble of thermal fluctuation records from 9 experimental runs due to the nonlinear nature of the processes and the finite length of the studied records, the fluid dynamical interpretation of the observed flow phenomena is relatively straightforward. The system is in the state of well-developed geostrophic turbulence, that yields a power-law scaling in the power spectra of the fluctuations in both the wavenumber- and the frequency domain. The characteristic size of the cyclonic and anticyclonic eddies (corresponding to warm and cold temperature anomalies, respectively) tends to decrease as the ‘meridional’ temperature gradient drops, in agreement with the theoretical expectations. In parallel, the zonal drift velocities decrease even faster during the process, therefore the characteristic timescale of ‘weather change’ at a fixed measurement location increases significantly. This timescale is of the same order as the typical response time of the flow to the changes in the forcing (baroclinic adjustment) therefore fluctuations were found to increase markedly in this spectral band.

This experimental demonstration may help to increase awareness of the fact that a climate-like dynamical system can undergo a transition towards larger variability even without noticeable effects on the temporal fluctuations of one particular realization. This message applies to the GCM community as well: climate variability information from a single numerical run (e.g. CO$_2$ doubling scenario) could be misleading as it does not necessarily represent the full complexity of the underlying ensemble dynamics.

References

Death and Revival of Chaos

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We investigate the death and revival of chaos under the impact of a monotonous time-dependent forcing that changes its strength with a non-negligible rate. Starting on a chaotic attractor it is found that the complexity of the dynamics remains very pronounced even when the driving amplitude has decayed to rather small values. When after the death of chaos the strength of the forcing is increased again with the same rate of change, chaos is found to revive but with a different history. This leads to the appearance of a hysteresis in the complexity of the dynamics. To characterize these dynamics, the concept of snapshot attractors is used, and the corresponding ensemble approach proves to be superior to a single trajectory description, that turns out to be nonrepresentative. The death (revival) of chaos is manifested in a drop (jump) of the standard deviation of one of the phase-space coordinates of the ensemble; the details of this chaos-nonchaos transition depend on the ratio of the characteristic times of the amplitude change and of the internal dynamics. It is demonstrated that chaos cannot die out as long as underlying transient chaos is present in the parameter space. As a condition for a "quasistatically slow" switch-off, we derive an inequality which cannot be fulfilled in practice over extended parameter ranges where transient chaos is present. These observations need to be taken into account when discussing the implications of "climate change scenarios" in any nonlinear dynamical system.

References

The Theory of Parallel Climate Realizations as a New Framework for Teleconnection Analysis

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Teleconnections are striking features of the Earth climate system which appear as statistically correlated climate-related patterns between remote geographical regions of the globe. In a changing climate, however, the strength of teleconnections might change, and an appropriate characterization of these correlations and their change (more appropriate than detrending the time series) is lacking in the literature. Here we present a novel approach, based on the theory of snapshot attractors, corresponding in our context to studying parallel realizations of the climate system. Imagining an ensemble of parallel Earth systems, instead of the single one observed on the real Earth, the ensemble, after some time, characterizes the appropriate probabilities of all options permitted by the climate dynamics, reflecting the internal variability of the climate. We claim that the relevant quantities for characterizing teleconnections in a changing climate are correlation coefficients taken over the temporally evolving ensemble in any time instant. As a particular example, we consider the teleconnections of the North Atlantic Oscillation (NAO). In a numerical climate model, we demonstrate that this approach provides the only statistically correct characterization, in contrast to commonly used temporal correlations evaluated along single detrended time series. The teleconnections of the NAO are found in the model to survive the climate change, but their strength is time-dependent.

References

Crisis of Pullback Strange Attractors in a Delay Differential Model of El Niño-Southern Oscillation

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The occurrence of a pullback strange attractor crisis is identified for a seasonally forced delay differential model of ENSO, with two delays. This crisis corresponds to a chaos-to-chaos transition as a control parameter crosses a critical value and is manifested by a brutal change in the shape of the pullback strange attractor as well as of the pullback statistical equilibrium it supports. These brutal changes are associated with the sudden disappearance of extreme El Niño/La Niña events, as one crosses the critical parameter value from below. The analysis reveals that regions of the pullback strange attractor that survive the crisis are those populated by the most probable states of the system. These regions are those exhibiting foldings that are the most robust to perturbations. The effects of noise on such a crisis will be discussed. It will be shown that the chaos-to-chaos crisis may not survive the addition of small noise to the evolution equation, depending on how the noise enters the latter.
Predicting Climate Change Using Response Theory: Global Averages and Spatial Patterns

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The provision of accurate methods for predicting the climate response to anthropogenic and natural forcings is a key contemporary scientific challenge. Using a simplified and efficient open-source general circulation model of the atmosphere featuring $O(10^5)$ degrees of freedom, we show how it is possible to approach such a problem using nonequilibrium statistical mechanics. Response theory allows one to practically compute the time-dependent measure supported on the pullback attractor of the climate system, whose dynamics is non-autonomous as a result of time-dependent forcings. We propose a simple yet efficient method for predicting—at any lead time and in an ensemble sense—the change in climate properties resulting from increase in the concentration of CO$_2$ using test perturbation model runs. We assess strengths and limitations of the response theory in predicting the changes in the globally averaged values of surface temperature and of the yearly total precipitation, as well as in their spatial patterns. The quality of the predictions obtained for the surface temperature fields is rather good, while in the case of precipitation a good skill is observed only for the global average. We also show how it is possible to define accurately concepts like the inertia of the climate system or to predict when climate change is detectable given a scenario of forcing. Our analysis can be extended for dealing with more complex portfolios of forcings and can be adapted to treat, in principle, any climate observable. Our conclusion is that climate change is indeed a problem that can be effectively seen through a statistical mechanical lens, and that there is great potential for optimizing the current coordinated modeling exercises run for the preparation of the subsequent reports of the Intergovernmental Panel for Climate Change.

References

Linear Response Theory Applied to Geoengineering

Tamás Bódai

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We investigate in an intermediate-complexity climate model the applicability of linear response theory to a geoengineering problem. Global climate change with respect to an appropriate ensemble average of the surface air temperature $T$ due to a given rise in carbon dioxide concentration $[\text{CO}_2]$ is attempted to be canceled out or modulated by an appropriately chosen modulation of the solar forcing. The latter is predicted by linear response theory in frequency-domain as:

$$\Delta f_s(\omega) = \frac{\Delta \langle T \rangle (\omega) \chi_{\text{CO}_2}(\omega) \Delta f_{\text{CO}_2}(\omega)}{\chi_s(\omega)},$$

where the $\chi$’s are linear susceptibilities.

With a doubling of $[\text{CO}_2]$ the response is nonlinear to a certain degree, but a significant cancellation with respect to ($\text{wrt.}$) $[T]$ is achieved, the asymptotic total response to combined forcing being only 10% of that with $[\text{CO}_2]$-doubling alone. We investigate in this geoengineering scenario the response $\text{wrt.}$ zonal or regional averages of $T$ too. The nonlinearities have a more severe effect $\text{wrt.}$ the predictability of the spatial total response pattern, but in actual fact a significant cancellation is achieved even locally. Similar conclusions can be drawn $\text{wrt.}$ the model variable of large scale precipitation.

The regional and global response can be characterized roughly by a single dominant multi-year time scale. The spatial pattern of the response time is rather nontrivial.
Pullback Attractors of a Low-order Ocean Model Subject to Periodic and Aperiodic Forcing

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A low-order quasigeostrophic model [1] captures several key features of intrinsic low-frequency variability of the oceans wind-driven circulation. This double-gyre model is used here as a prototype of an unstable and nonlinear dynamical system with time-dependent forcing to explore basic features of climate change in the presence of natural variability. The studies rely on the theoretical framework of nonautonomous dynamical systems and of their pullback attractors (PBAs), namely the time-dependent invariant sets that attract all trajectories initialized in the remote past [2,3]. Ensemble simulations help us explore these PBAs.

The chaotic PBAs of the periodically forced model [4] are found to be cyclo-stationary and cyclo-ergodic. Two parameters are then introduced to analyze the topological structure of the PBAs as a function of the forcing period; their joint use allows one to identify four distinct forms of sensitivity to initial state that correspond to distinct system behaviors. The model’s response to periodic forcing turns out to be, in most cases, very sensitive to the initial state.

The system is then forced by a synthetic aperiodic forcing [5]. The existence of a global PBA is rigorously demonstrated. We then assess the convergence of trajectories to this PBA by computing the probability density function (PDF) of trajectory localization in the models phase space. A sensitivity analysis with respect to forcing amplitude shows that the global PBA experiences large modifications if the underlying autonomous system is dominated by small-amplitude limit cycles, while the changes are less dramatic in a regime characterized by large-amplitude relaxation oscillations. The dependence of the attracting sets on the choice of the ensemble of initial states is then analyzed. Two types of basins of attraction coexist for certain parameter ranges; they contain chaotic and nonchaotic trajectories, respectively. The statistics of the former does not depend on the initial states, whereas the trajectories in the latter converge to small portions of the global PBA. This complex behavior requires, therefore, separate PDFs for chaotic and nonchaotic trajectories. Finally, the extension of [5] to the case of random dynamical systems is outlined.

References

Plankton-climate Interaction in Climate Change

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We would like to model, in association with the greenhouse effect, the contribution of the CO₂ content to the pole-equator temperature contrast. Our aim is to couple a simple atmospheric dynamics to that of the photosynthetizing biomass, assumed to be dominated by plankton. The temperature contrast thus also depends on the plankton concentration. The plankton concentration is assumed to follow a logistic evolution in which the carrying capacity is taken to depend both on the temperature contrast and on the turbulence level in the upper layer of the ocean. We explore, in the spirit of snapshot attractors, how the presence of plankton influences the dynamics of the climate change, and we compare it to the case where the interaction with the biomass is negligible.

References

This talk is based on a joint work with D. Prokaj, I. Scheuring and T. Tél.
Generalized Lorentz Equations

James A. Yorke

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Edward N. Lorenz is best known for one specific three-dimensional differential equation, but he actually created a variety of related N-dimensional models. I will discuss a unifying principle for these models and put them into an overall mathematical framework. Because this family of models is so large, we are forced to choose. We sample the variety of dynamics seen in these models, by concentrating on a four-dimensional version of the Lorenz models for which there are three parameters and the norm of the solution vector is preserved. We can therefore restrict our focus to trajectories on the unit sphere in four dimensions. Furthermore, we create a type of Poincaré return map. We choose the Poincaré surface to be the set where one of the variables is 0, i.e., the Poincaré surface is a two-sphere in three dimensions. Examining different choices of our three parameters, we illustrate the wide variety of dynamical behaviors, including chaotic attractors, period-doubling cascades, Standard-Maplike structures, and quasi-periodic trajectories. Note that neither Standard-Maplike structure nor quasi-periodicity has previously been reported for Lorenz models.

Acknowledgment

This talk is based on joint work with E. Sander and Y. Saiki.
Stability in Non-autonomous Complex Dynamics (MS13)

Organizer: Aneta Stefanovska

Time-varying Kuramoto model

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Biological examples provided the original motivation lying behind the Kuramoto model (KM) of coupled phase oscillators [1]. However, neither the original model, nor any of its extensions [2], have incorporated a fundamental property of living systems – their inherent time-variability. Many important characteristics of open systems can be missed by not accounting for the non-equilibrium dynamics that stems from their time-dependent parameters.

We introduce a generalization of the KM by explicit consideration of deterministically time-varying parameters [3]. The oscillators’ natural frequencies and/or couplings are influenced by identical external force with constant or distributed strengths. The new dynamics of the collective rhythms consists of the external system superimposed on the autonomous one, a characteristic feature of many thermodynamically open systems. This deterministic, stable, continuously time-dependent, collective behavior is fully described. Additionally the external impact and the reduced dynamics are defined in both the adiabatic and non-adiabatic limits. In this way, a large range of systems tackled by the Kuramoto model – spanning from a single cell up to the level of brain dynamics – can be described more realistically.

Further extension of the model that considers the effect of delay in couplings is also considered [4]. A collective dynamics arises from the interplay between the time scales of the original system, the external forcing, and the delays. This complex low-dimensional dynamics is described, uncovering an echo effect near the synchronization threshold.

The work to be presented helps to describe time-varying neural synchronization as an inherent phenomenon of brain dynamics. It accounts for experimental results [5, 6] and it extends and complements a previous attempt [7] at explanation.

References

Nonautonomic Perturbation Stabilizes Dynamics of Complex System

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Complex oscillatory dynamics appears everywhere, and on every scale, in nature. Phase synchronization \cite{ Pikovsky-book} of such oscillations plays an important role in a wide variety of applications spanning from the natural and life sciences to engineering. Although such oscillations with deterministically time-varying frequencies have been shown to exist experimentally, e.g. in the cardiovascular system \cite{Bracic-2000}, little is known theoretically about their properties \cite{Suprunenko-2013}. The description of dynamics with a time-varying frequency requires a non-autonomous \cite{Kloeden-2011} driving system, which is harder to treat theoretically. On the other hand, the non-autonomous case is very general, and its consideration is necessary in situations where an open system is influenced by a time-varying environment.

To fill this gap, we have investigated the dynamics of an oscillator subject to external periodic forcing with a periodically time-varying frequency. We have studied the average and short term stability of the system via numerical computation of the asymptotic and finite-time Lyapunov exponents. Furthermore, we have analyzed the system analytically in the limit of slow modulation.

We have shown that the size of the synchronization region in parameter space is increased proportionally to the frequency modulation, making the system more stable. Moreover, the non-autonomicity results in changes to the stability of the system over short-time scales, thus explaining the expansion of the synchronization region. Finally, we have also described the evolution of the frequency content over time, and tested this against time-frequency analysis of simulated trajectories.

Future work will include extension of this system to even more general time-varying driving, for which we expect the stabilizing effect to be similar. This type of system is very general, and has a wide range of applications to real life.

References

\cite{ Pikovsky-book}
\cite{Bracic-2000}
\cite{Suprunenko-2013}
\cite{Kloeden-2011}
Non-autonomous Delay-differential Models of the El Niño-Southern Oscillation and Their Pullback Attractors

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The El Niño/Southern Oscillation (ENSO) dominates intrinsic climate variability on the interannual time scale. Its rich dynamics involves two self-sustained oscillatory modes, quasi-biennial and quasi-quadrennial, along with the seasonal cycle that interacts with the internal variability and leads to phase locking. The name “El Niño” (for the Christ child) arises from the phase locking manifest in the timing of so-called warm, or El Niño, events in boreal winter, close to Christmas.

The physics of this phenomenon is dominated by coupling between the Tropical Pacific and the atmosphere above, and it is significantly affected by delays that arise from the travel time of equatorially trapped waves between the eastern and western boundaries of the Pacific basin. The latter aspect of the physics has led to the broad use of delay-differential [4, and references therein] and Boolean delay [3] equations in modeling ENSO.

We briefly review a simple delay-differential model of the sea surface temperature $T$ in the Tropical Pacific [4]. The model includes three essential mechanisms of ENSO dynamics: the seasonal forcing, the negative feedback due to the oceanic waves, and the delay caused by their propagation across the Tropical Pacific. This model’s rich behavior was studied via stability and bifurcation analysis in the three-dimensional (3-D) space of its physically most relevant parameters: the strength $b$ of the seasonal forcing, the atmosphere-ocean coupling parameter $\kappa$, and the characteristic propagation time $\tau$ of oceanic waves.

The model’s behavior exhibits phase locking to the seasonal cycle, namely the local maxima and minima of $T$ tend to occur at the same time of the year; this locking is a characteristic feature of the observed El Niño (warm) and La Niña (cold) events. Multiple model solutions coexist, and we describe their basins of attraction.

To shed further light on the parameter regimes in which the dynamics is quite complex, we examine the models pullback attractors [5]. This study helps clarify the nature of the interaction between the seasonal forcing and the models internal variability.

Acknowledgment
The talk represents joint work with M.D. Chekroun, H. Liu, J.D. Neelin, S. Wang and I. Zaliapin.

References
A dynamical system is said to undergo rate-induced tipping when it fails to track its quasi-equilibrium state due to an above-critical-rate change of system parameters. We study a prototypical model for rate-induced tipping, the saddle-node normal form subject to time-varying equilibrium drift and noise. We find that both most commonly used early-warning indicators, increase in variance and increase in autocorrelation, occur not when the equilibrium drift is fastest but with a delay. We explain this delay by demonstrating that the most likely trajectory for tipping also crosses the tipping threshold with a delay and therefore the tipping itself is delayed. We find solutions of the variational problem determining the most likely tipping path using numerical continuation techniques. The result is a systematic study of the most likely tipping time in the plane of two parameters, distance from tipping threshold and noise intensity.
Dynamics of Cellular Energy Metabolism

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In order to persist, a living biological system must have certain stability properties. Signatures of such properties are: inner processes in a living system adjusting to the time-varying environment, and a living system maintaining its function by resisting external perturbations. In this talk we define and study stability properties of the dynamics of cellular energy production – a crucially important process in living systems.

Due to the thermodynamic openness of a living cell, fluctuating supply and demand in energy metabolism cannot be instantaneously matched, which results in non-autonomous oscillatory dynamics. Based on experimental evidence of metabolic oscillations, we show that stability properties of cellular energy metabolism can be described in terms of the recently introduced theory of chronotaxic systems, which describes non-autonomous oscillatory dynamical systems with contraction properties resulting in the existence of a time-dependent point attractor.

First, we present a method for the identification of chronotaxicity, i.e. the ability of a non-autonomous oscillator to resist external perturbations. This method is applicable to general oscillatory signals. Second, applying this method to experimental data of glycolytic oscillations in real yeast cells we verify the applicability of chronotaxicity to metabolic oscillations. We build a model which is focused on the chronotaxicity of cellular energy metabolism. As a result, we show that chronotaxicity could be used to study transitions between healthy and abnormal metabolic states. This is particularly important because altered states of cellular energy metabolism represent a hallmark of many diseases, one notable example being cancer. Finally, we show that alterations in the chronotaxicity of the corresponding metabolic oscillations can describe robustly the transition from healthy to abnormal metabolic states.
Synchronization Patterns in Networks: Theory and Applications (MS14)

Organizers: István Z. Kiss and Oleh Omel’chenko

The Effects of Noise on an Oscillator Ensemble Coupled in a Star-graph Configuration

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Noise induced synchronization occurs when an ensemble of uncoupled nonlinear, autonomous oscillators is subjected to a broad-band correlated forcing, e.g. noise [1]. It is a surprising insight that noise can have both, a constructive effect on synchronization and a desynchronizing effect. Here we report on our investigation of the influence of noise in oscillators coupled through a pace-maker center on a star-graph. Indeed, noise in the peripheral nodes may destroy the explosive first order transition to synchronization [2] all together while noise in the center node can induce stability of complete synchronization. We hypothesize that these competing mechanisms of desynchronizing noise in the bulk and synchronizing noise in the hubs may play a role in the synchronization transition on scale-free networks.

References

Optimal Network Motif for Synchronization in Coupled Noisy Oscillators

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Synchronization of rhythmic elements is ubiquitously found in nature. In biology, synchronization plays a vital role in biological functions, such as circadian clocks, heartbeats, somite formation, to name a few. Although rhythmic elements are noisy in many cases, they are required to be well synchronized. It is therefore important to understand the design principle for good synchronization. In this talk, we examine the network structure dependence of synchronizability of coupled phase oscillators subjected to noise, described by

$$\dot{\phi}_i(t) = \omega + \sum_j A_{ij} \sin(\phi_j - \phi_i) + \xi_i(t),$$

where $\phi_i$ ($1 \leq i \leq N$) is the phase of the $i$th oscillator and $\omega$ is the natural frequency; $\kappa$ is the overall coupling strength; $A_{ij}$ is the weight of the directed edge from the $j$th oscillator to the $i$th oscillator; and $\xi_i$ is the independent white Gaussian noise with generally heterogeneous noise intensities. Using linear approximation valid for weak noise, we obtain the expression for the expected value of the Kuramoto order parameter as a function of eigenvalues and eigenvectors of network Laplacian. We show several examples of networks composed of a few elements and discuss optimal network motif based on our theory.
Echo Behavior in Large Populations of Chemical Oscillators

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Experimental and theoretical studies are reported 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 $\tau$ after the perturbation (where $\tau$ 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 $2\tau$, $3\tau$, ... 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.

References

Pulsatile Delayed Feedback for Closed-loop Deep Brain Stimulation

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High-frequency (HF) deep brain stimulation (DBS) is the standard treatment of medically refractory movement disorders like Parkinson’s disease, essential tremor, and dystonia, with a significant potential for application to other neurological diseases. The standard setup of HF DBS utilizes an open-loop stimulation protocol, where a permanent HF electrical pulse train is administered to the brain target areas irrespectively of the ongoing neuronal dynamics. Recent experimental and clinical studies demonstrated that a closed-loop, adaptive DBS might be superior to the open-loop setup. We here extend the delayed feedback stimulation methods, which are intrinsically closed-loop techniques and specifically designed to desynchronize abnormal neuronal synchronization, to pulsatile electrical brain stimulation. For this, the amplitude of the HF train of biphasic charge-balanced electrical pulses used by the standard HF DBS is modulated by the smooth feedback signals of linear or nonlinear delayed feedback methods. Such stimulation signals preserve the desynchronizing delayed feedback characteristics and comply with mandatory charge deposit-related safety requirements. We show that such a pulsatile delayed feedback stimulation can effectively and robustly desynchronize a network of model neurons comprising subthalamic nucleus (STN) and globus pallidus external (GPe) and suggest this approach for desynchronizing closed-loop DBS. We also show that an interphase gap introduced between the recharging phases of the charge-balanced biphasic pulses can significantly improve the stimulation-induced desynchronization and reduce the amount of the administered stimulation. Our results may contribute to a further development of effective stimulation methods for the treatment of neurological disorders characterized by abnormal neuronal synchronization.
Inter-layer Relay Synchronization in Multiplex Networks

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Inter-layer synchronization is an interesting dynamical process occurring in multi-layer networks. This process emerges when every node is synchronized with its counterparts in other layers, while nodes in each layer do not necessarily evolve in unison. Inter-layer synchronization has been very recently demonstrated in layers with identical \cite{Sevilla-Escoboza2016} and non-identical \cite{Leyva2017} connectivity structure. An analysis based in the master stability function allows to reduce the dimensionality of the system and predicts the conditions for inter-layer synchronization.

In the work we report the details of an numerical, analytical and experimental study of inter-layer relay synchronization in a multiplex network. Relay synchronization, previously studied mainly in single dynamical systems, consists of achieving complete synchronization of two systems by indirect coupling through a relay unit, whose dynamics does not necessary join the synchronous state.

We extend this concept to multilayer systems, showing the conditions for achieving this state and how it can be predicted by means of a MLE-like treatment. We show that this state is very robust to structural and dynamical variations in the relay layer, and that it can be maintained even in the case where a large proportion of the nodes are demultiplexed. Finally, by the use of multiplexed layers of electronic circuits, we study the phenomenon a a function of the dynamical conditions of the nodes and the structure of the layers. This results are very relevant in the study of long distance synchronization in brain, where it is well know that equivalent areas in both brain hemispheres reach highly coherent states through their mutual connection to a intermediation area.

References

Noninvasive Model Reconstruction from a Partially Synchronized State

Oleh Omel’chenko\textsuperscript{1}, Michael Sebek\textsuperscript{2}, and István Z. Kiss\textsuperscript{2}

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\textsuperscript{2} Department of Chemistry, Saint Louis University, St Louis, USA

In this talk, we suggest an algorithm for complete reconstruction of the parameters of the Kuramoto-Sakaguchi model, i.e., mathematical model of globally coupled phase oscillators with a phase lag. Our method relies on the fitting of the time-averaged quantities usually available in experiments to some universal relations known from the continuum limit analysis. The accuracy of the method grows for the increasing system size and is almost independent of the system parameters provided one examines a well-developed partially synchronized state. We illustrate our theoretical predictions with an application of the method to parameter reconstruction of a system of electrochemical oscillators.
Chimera States in Nonlocally Coupled Oscillators

*Edgar Knobloch*

Department of Physics, University of California, USA

In this talk I will describe recent work on (a) phase-coupled oscillators of Kuramoto type and (b) coupled Stuart-Landau oscillators, both with nonlocal coupling, focusing on chimera states. I will describe conditions under which chimera states are present in both systems, and their stability properties as a function of the system parameters. The results will be compared with numerical simulations of both systems.
Experimental Observation of Spiral Wave Chimeras in Coupled Chemical Oscillators

Jan Frederik Totz\textsuperscript{1}, Ken Showalter\textsuperscript{2}, and Harald Engel\textsuperscript{1}

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In populations of coupled nonlinear oscillators, synchronization and macroscopic non-equilibrium pattern formation are intrinsically linked. In 2002, studying synchronization of nonlocally coupled oscillators, Kuramoto and coworkers made a remarkable observation [1]: Although both the natural frequency of the individual oscillators as well as their coupling among each other were identical, for certain initial conditions some oscillators became phase-synchronized while others did not. The discovery of this counterintuitive state, named chimera state by Steven Strogatz [2], triggered an increasing number of studies on partial synchronization [3].

We will present a versatile setup based on optically coupled catalytic micro-particles, that allows for the experimental study of synchronization patterns in very large networks of relaxation oscillators under well-controlled laboratory conditions. In particular, we will show our experimental observation of the spiral wave chimera, predicted by Kuramoto in 2003 [4]. This pattern features a wave rotating around a spatially extended core that consists of phase-randomized oscillators. We study its existence depending on coupling parameters and observe a transition to incoherence via core growth and splitting. The spiral wave chimera is likely to play a role in cardiac [3] and cortical cell ensembles [5], as well as in cilia carpets [6].

References

Pulse-coupled Chemical Oscillators: Experiments, Models, Theory

Viktor Horvath, Daniel J. Kutner, and Irving R. Epstein

Department of Chemistry, Brandeis University, Waltham, USA

Two identical pulse-coupled Belousov-Zhabotinsky (BZ) oscillators display various modes of synchronization as well as other interesting dynamical phenomena, like bursting and oscillatory death when coupling strengths match. When the intrinsic frequencies of the two coupled oscillators initially match but the coupling strengths are unequal, this system may display phase locked oscillations, or stable temporal patterns where the frequencies of the oscillators no longer match, or oscillator death [1]. Similar behavior can be observed when the natural frequencies of the oscillators are significantly different and the coupling strengths are equal [2, 3]. Numerical simulations using a model based on mass action kinetics show domains of various entrainment modes 1:1, 3:4, 2:3, 2:5, 1:2, 1:3, 1:4, etc., which correspond to the experimental observations.

We have characterized the dynamics of pulse-perturbed BZ oscillators, and found that the frequency is affected by inhibitory perturbations in the long term. Using a simpler, phase frequency model we were able to reproduce the experimental observations. We have developed a method to find the constraints that the control parameters (coupling strengths, natural frequencies) must obey in order to produce the experimentally observed behaviors. Our approach is general, and therefore it may be applicable to other systems where individual units coupled via short pulses, such as networks of neurons.

References

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

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When electrochemical reactions take place on electrode arrays, a network can form through the potential drop among the elements. Such networks can generate spatially organized partially synchronized states using oscillatory chemical reactions with two fundamental mechanisms [1-2]. In oscillations with nearly identical natural frequencies, we describe the emergence of chimera states. The experiments point out the importance of low level of heterogeneities (e.g., surface conditions) and optimal level of coupling strength and time-scale as necessary components for the realization of the chimera state. For experimental conditions where chimera states are not possible, we analyze the spatially organized partially synchronized states as a function of underlying heterogeneities and network topologies. As a prototype system, we consider three oscillators with superimposed local and global coupling topologies. An analytical formula is derived for the mixed local/global coupling topology for the critical coupling strength at which full synchrony is achieved. The formula is verified with experiments using electrochemical oscillator networks.

References

Efficient Terahertz-wave Generation and Detection Based on Dynamic Nonlinear Effect

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Terahertz (THz) waves have attracted a great deal of interest for a growing number of applications including spectroscopy, imaging, and sensing. Recent progress in nonlinear photonics has made considerable advances in THz-wave technology for powerful sources and sensitive detectors. In particular, using MgO:LiNbO$_3$ nonlinear crystal which possesses a large figure of merit for wavelength-conversion in THz-wave range, intense THz-wave emission of more than 100-kW peak power and attojoule-level sensitive detection of THz-wave pulse energy have been demonstrated with sub-nanosecond giant-pulsed microchip Nd:YAG lasers. This talk describes recent our studies on intense THz-wave emission, highly sensitive THz-wave detection, and real-time THz-wave imaging based on nonlinear optical effects [1-10].

Acknowledgment

We would like to thank Prof. H. Ito of RIKEN/Tohoku Univ. and Prof. M. Kumano of Tohoku Univ. for useful comments and Dr. T. Taira of IMS and Prof. K. Kawase of Nagoya Univ. for collaboration works. We are also grateful to all members of the Tera-Photonics Research Team, RAP, RIKEN. This work was partially supported by JSPS KAKENHI Grant Numbers 15K18079, 25220606, 26390106, 26620162, 15K18080, 26246046, 26287067, 25286075 and ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

References

Terahertz Time-domain Coherent Raman Spectroscopy Using Picosecond Frequency-chirped Optical Pulses

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This paper reports on coherent Raman spectroscopy in the terahertz frequency region by using picosecond frequency-chirped optical pulses. The unique properties as well as the principle of this technique are explained. This method is simple and useful to study low frequency (< 20 THz) atomic and molecular dynamics in solids, liquids and aqueous solutions.

When two identical frequency-chirped optical pulses are overlapped, they create an optical beat whose beating frequency is depending on the relative time-delay between the two optical pulses. This optical beat can be used for excitation of molecules. When the optical beat frequency coincides with a vibration frequency of molecules under excitation, the energy of the light with higher frequency is transferred to that of lower frequency due to the third-order nonlinear optical process (coherent Raman scattering). By observing the increase (stimulated Raman gain) or decrease (stimulated Raman loss or inverse Raman) in one of the optical beams used for excitation, we can get a coherent Raman spectrum of the molecules in time-domain. This "Terahertz Time-Domain Coherent Raman Spectroscopy" is useful for observation of picosecond molecular dynamics and weak molecular interactions Terahertz Time-Domain Coherent Raman Spectroscopy, such as hydrogen bondings. Several examples of coherent Raman spectra measured with this technique, such as for DMSO, CCl\textsubscript{4}, and water solution of ZnBr\textsubscript{2}, etc. are presented.
The terahertz and optical regions of the electromagnetic spectrum each present specific properties that have led to numerous applications. We present results exploiting each one of these regions.

Terahertz waves can penetrate non-conducting materials such as plastics, coatings, and certain composites. Exploiting these properties, we show different examples of how terahertz time-domain spectroscopy can be used for nondestructive evaluation. In particular, we identify deep delaminations in glass-fiber reinforced composites [1], distinguish between inter- and intra-laminar impact damage by exploiting the sensitivity of the material to the polarization of the THz field [2], identify corrosion areas in polymer-coated steel [3], and resolve the different paint layers of an art painting [4].

Optical dynamical systems are great testbeds for exploring fast, sub-nanosecond, nonlinear dynamics and their applications. We study experimentally the dynamics of one of the most important optical dynamical systems, namely the laser diode subjected to external optical feedback. We demonstrate experimentally the sequence of bifurcations that occur in its route to chaos [5] and discover that different bifurcation diagrams can be obtained by making use of the multistability of the laser diode [6]. Finally, by exploiting the properties of the chaotic regime, we show how compressive sensing at a high-speed can be implemented [7].

References

Mode Competition Dynamics in Micro Cavity Lasers

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Various active devices ranging from musical instruments to lasers generate self-organized oscillating states with well-defined frequencies from the interplay between resonator geometry and an active nonlinear element; resonator determines the oscillating modes and they are amplified by an active nonlinear element inside the resonator. The active nonlinear element also has a crucial role in selecting a final oscillating state by inducing competitive interaction among the modes. Understanding and controlling the formation of such oscillating states is important in device physics and related applications.

In our talk, we focus on mode-competition in microcavity lasers [1] and report our recent finding that the degree of mode competition and the resulting lasing states can be controlled by the resonator geometry [2]. In particular, we experimentally and theoretically show that when the laser resonator is so-called chaotic cavity, stable single-mode lasing can be achieved by strong mode competition, whereas in non-chaotic cavities, multimode lasing is exhibited due to weak mode competition.

References

Chaotic Oscillation of Laser Diode with Optical Injection and Pseudorandom Signal

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2 Waseda University, Japan  
3 Tokyo University of Science, Japan

There has been some interest in the chaotic dynamics of laser diodes (LDs) because of its potential applications in chaotic secure communications. To achieve encoded and decoded messages, broadband spectra and chaos synchronization are mainly utilized [1, 2]. On the other hand, we have proposed a digital secure communication scheme based on the orbital instability of a chaotic laser, which is a hardware-dependent scheme and does not depend on chaos synchronization [3]. In this scheme, a binary digit is defined by the dynamics of two different chaotic systems. To reduce the bit error rate in this scheme, it is necessary to vary the chaotic dynamics to make the difference between the orbital instability of the two systems larger than the perturbation caused by external noise. In this study, we numerically investigate the chaotic oscillation of an LD system with optical injection and show that the orbital instability of the slave LD can be controlled by applying a pseudorandom signal to the drive current.

The dynamics of an optical injection LD system with a pseudorandom signal, which consists of a master LD and a slave LD injected into the master LD unidirectionally, can be described by rate equations [1, 4]. In these equations, the drive current is written as $p \cdot (m(t) + 1) \cdot J_{th}/2$, where $J_{th}$ is its value at the solitary laser threshold. The applied pseudorandom signal is denoted as $m(t)$, which has a normal distribution with a mean of 1 and a standard deviation of $\sigma$. Then, the orbital instability of the slave LD is quantified by the Lyapunov exponent [5, 3].

First, we consider the Lyapunov exponent $\lambda$ of the slave LD at injection coefficient $\eta = 35 \ [\text{ns}^{-1}]$ when pseudorandom signals with standard deviations of $\sigma_1$ and $\sigma_2$ are applied to the drive currents of the master and slave LDs, respectively. The Lyapunov exponent gradually increases with increasing $\sigma_1$ because of the enhanced modulation bandwidth caused by parameter mismatch between the master and slave LDs. On the other hand, $\lambda$ slightly increases with increasing $\sigma_2$ because of relaxation oscillation in the slave LD.

Next, we consider the Lyapunov exponent $\lambda$ of the slave LD when a pseudorandom signal with a standard deviation of 1 is applied to the drive current of the master LD, and the drive current of the slave LD has no signal. For a small injection coefficient ($\eta < 25 \ [\text{ns}^{-1}]$), $\lambda$ slightly increases with increasing $\sigma_1$. However, as $\eta$ increases, $\lambda$ more rapidly increases with increasing $\sigma_1$. The results show that the chaotic dynamics can be controlled by applying a pseudorandom signal to the drive current of the master LD in the case of large injection coefficient ($\eta > 35 \ [\text{ns}^{-1}]$), and that this enables the possibility of a digital secure communication scheme based on orbital instability.

References

Contributed talks
Mathematical Aspects (CT16)

Discussion leader: Tibor Krisztin

Tuesday 17:40 – 18:00 (Room 107)

Asymptotic of Solution of Nonlinear Equation with Two Large Delays

Ilia Kashchenko

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Consider equation with two large delays

\[ \dot{x} + ax(t - T) + bx(t - T_1) + f(x, x(t - T), x(t - T_1)), \quad T_1 > T > 0. \]

Here \( a \) and \( b \) are some constants, \( f(x, y, z) \) is nonlinear function. The main assumption is that delay times \( T \) and \( T_1 \) are sufficiently large and proportional each other:

\[ T = \varepsilon^{-1}, \quad T_1 = T(k_0 + \varepsilon^{\alpha}k_1), \quad 0 < \varepsilon \ll 1, \quad k_0 \geq 1, \quad \alpha > 0. \]

The problem to research is to determine the behaviour of solutions in some small (but independent of \( \varepsilon \)) neighbourhood of zero equilibrium state and built the asymptotic for stable solutions.

It will be shown that algebraic properties of \( k_0 \) is very important. Results are different for rational and irrational \( k_0 \). Also, even the results on the stability of zero are significantly influenced by the values of \( \alpha \). So cases \( \alpha < 1 \), \( \alpha = 1 \) and \( \alpha > 1 \) will be studied separately.

It’s proved that all critical cases have infinite dimension. For rational \( k_0 \) further investigation [1] was performed using the method of quasinormal forms. The main idea of this method is to construct a special substitution by means of which the initial equation reduces to a problem that does not contain small parameters (or depends on them regularly). This problem (the quasinormal form), unlike the initial equation, can easily be investigated numerically.

In all cases quasinormal forms are given and explicit formulas that connect the solutions of the original problem and the quasinormal form are presented. It turned out that normalized problems are nonlinear equations of parabolic type. In the case \( \alpha > 1 \), the space variable in these equations is one-dimensional, and for \( \alpha \leq 1 \), it is two-dimensional.

An important fact is the presence in quasinormal forms of arbitrary parameters (absent in the original equation). When these parameters change, we get another normalized problems, another their solutions and another solutions of the original equation. This indicates the presence of the phenomenon of multistability in the equation with two large delays.

References

Ordinal Network Based Time Series Analysis Using Geodesic Measures

Michael McCullough¹, Michael Small¹,²,³, Thomas Stemler¹,², and Herbert Ho-Ching Iu⁴,²

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Network-based methods for the analysis of nonlinear time series provide a novel means of extracting useful information from data measured from complex systems [1, 2]. The defining principle of such methods is that time series data is used to generate a network, the structural properties of which are then analyzed using measures from the field of network science to infer dynamical properties of the system from which the time series was measured. Recently, we proposed an approach which we call the method of ordinal networks [3], whereby an ordinal partition [4] is applied to a time delay embedding of the data to construct a sequence of symbols which is then consolidated into a Markov chain. Our preliminary results demonstrated that the structure of an ordinal network is sensitive to the underlying dynamics of the time series, and that simple metrics on a binary reduction of the network can quantify relative changes in these dynamics.

In this study we continue our investigations by considering the complete weighted and directed ordinal network. We apply the well known property that the diameter of a Markov chain is a lower bound to the mixing time of the system [5, 6] to derive a new measure which we call the normalized ordinal network diameter. This measure is an estimate of the mixing time of the network model relative to the size of the network. The inverse of this measure provides a dimensionless quantity related to the rate at which a system mixes. Under the assumption of determinism, it is intuitive that this inverse measure should be related to the largest Lyapunov exponent which quantifies the rate at which chaotic systems become unpredictable by the process of exponential divergence of trajectories.

To assess the performance of the new measure we perform a numerical investigation using simulated time series data from the Muthuswamy-Chua system with a quadratic nonlinearity [7] which is characterized by single scroll chaotic attractor; and a modified version of the Muthuswamy-Chua system with a fourth order polynomial nonlinearity [8] which is characterized by a four scroll chaotic attractor. We compare the inverse normalized ordinal network diameter with estimates of the largest Lyapunov exponent computed using Sano and Sawadas algorithm [9, 10] for a range of the bifurcation parameter in each system. Our results demonstrate that the new measure consistently and accurately tracks the relative change in the largest Lyapunov exponent through bifurcations and periodic windows. The exceptions are time series exhibiting Pomeau-Manville intermittency [11] where the new measure appears to have bias towards quantifying the chaotic portion of the data, being less sensitive to the intermittent periodic behavior than the largest Lyapunov exponent.

Acknowledgment

MS is supported by the Australian Research Council Discovery Project DP 140100203.

References

Cubic Homoclinic Tangency and Complex Structures of Periodicity in Planar Parameter Space

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\textsuperscript{3} Mathematical Department, Lobachevsky State University of Nizhny Novgorod, Russia

Structures of periodicity in the parameter space have called the attention of the scientific community of dynamical systems in these last years. The importance comes from what kind of behavior is expected when the parameter space is perturbed with several implications in biology, engineering, and physics. In this talk it will be presented the scenery in the parameter space when a cubic homoclinic tangency occur in the phase space. In special, we deduce the normal form of one of the most largely observed structure in dissipative systems, the cockroach. We also show the complex sets of periodicity and chaoticity promoted by its presence and show the role of homoclinic orbits in the shape of cockroaches.
Exploiting Delay Coordinates for Data Assimilation and Parameter Estimation

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Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany

Delay coordinates are not only fundamental for attractor reconstruction in Nonlinear Time Series Analysis but also provide comprehensive dynamical information for other applications. As examples we consider the task of parameter estimation from time series (including estimability analysis [1-4]) and advanced schemes for achieving synchronization [4,5] with applications in data assimilation. These approaches will be illustrated using different dynamical systems including the high dimensional Lorenz-96 model.

References

Variety of Integrable Cases in Dynamics of Nonconservative Variable Dissipation Systems

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We study nonconservative systems for which the usual methods of the study, e.g., Hamiltonian systems, are inapplicable. Thus, for such systems, we must "directly" integrate the main equation of dynamics. We generalize previously known cases and obtain new cases of the complete integrability in transcendental functions of the equation of dynamics of a four-dimensional rigid body in a nonconservative force field.

Of course, in the general case, the construction of a theory of integration of nonconservative systems (even of low dimension) is a quite difficult task. In a number of cases, where the systems considered have additional symmetries, we succeed in finding first integrals through finite combinations of elementary functions [1, 2].

We obtain a series of complete integrable nonconservative dynamical systems with nontrivial symmetries. Moreover, in almost all cases, all first integrals are expressed through finite combinations of elementary functions; these first integrals are transcendental functions of their variables. In this case, the transcendence is understood in the sense of complex analysis, when the analytic continuation of a function into the complex plane has essentially singular points. This fact is caused by the existence of attracting and repelling limit sets in the system (for example, attracting and repelling focuses).

We detect new integrable cases of the motion of a rigid body, including the classical problem of the motion of a multi-dimensional spherical pendulum in a flowing medium.

This activity is devoted to general aspects of the integrability of dynamical systems with variable dissipation. First, we propose a descriptive characteristic of such systems. The term "variable dissipation" refers to the possibility of alternation of its sign rather than to the value of the dissipation coefficient (therefore, it is more reasonable to use the term "sign-alternating").

We introduce a class of autonomous dynamical systems with one periodic phase coordinate possessing certain symmetries that are typical for pendulum-type systems. We show that this class of systems can be naturally embedded in the class of systems with variable dissipation with zero mean, i.e., on the average for the period with respect to the periodic coordinate, the dissipation in the system is equal to zero, although in various domains of the phase space, either energy pumping or dissipation can occur, but they balance to each other in a certain sense. We present some examples of pendulum-type systems on lower-dimension manifolds from dynamics of a rigid body in a nonconservative field.

Then we study certain general conditions of the integrability in elementary functions for systems on the two-dimensional plane and the tangent bundles of a one-dimensional sphere (i.e., the two-dimensional cylinder) and a two-dimensional sphere (a four-dimensional manifold). Therefore, we propose an interesting example of a three-dimensional phase portrait of a pendulum-like system which describes the motion of a spherical pendulum in a flowing medium (see also [13]).

References

Collocated POD and Simulation of Nonlinear Dynamics

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Proper Orthogonal Decomposition (POD) is a well-known reduction technique yielding an optimal linear basis of a set of vectors (snapshots), which proves to be effective in a variety of applications, from data processing tasks to the low dimensional description of complex systems governed by partial differential equations.

In this work, a new sampling strategy is proposed as a preliminary step to POD in order to enhance its efficiency. The main idea consists in performing an incomplete LU decomposition (with pivoting) of the snapshot matrix to select a set of appropriate snapshots and a set of collocation points (snapshot components) that maximize the linear independency among the original data. Then, POD is applied to the selected snapshots using a reduced inner product based on the collocation points only. The resulting method [1] is computationally cheap, accurate, and more efficient than standard POD.

The performance of the collocated POD is illustrated in different applications, including its combination with Galerkin projection to construct reduced order models for the fast simulation of time dependent nonlinear dynamics and fairly complex bifurcation diagrams, in the spirit of [2, 3].

References

Population Dynamics of Epidemic and Endemic States of Drug-resistance Emergence in Infectious Diseases with Delayed Treatment Initiation

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¹ University of Szeged, Hungary
² University College London, UK
³ York University, Canada

The emergence and spread of drug-resistance during treatment of many infectious diseases continue to degrade our ability to control and mitigate infection outcomes using therapeutic measures. While the coverage and efficacy of treatment remain key factors in the population dynamics of resistance, the timing for the start of the treatment in infectious individuals can significantly influence such dynamics. We developed a between-host disease transmission model to investigate the short-term (epidemic) and long-term (endemic) states of infections caused by two competing pathogen subtypes, namely the wild-type and resistant-type, when the probability of developing resistance is a function of delay in start of the treatment. We characterize the behaviour of disease equilibria and obtain a condition to minimize the fraction of population infectious at the endemic state in terms of probability of developing resistance and its transmission fitness. For the short-term epidemic dynamics, we illustrate that depending on the likelihood of resistance development at the time of treatment initiation, the same epidemic size may be achieved with different delays in start of the treatment, which may correspond to significantly different treatment coverages. Our results demonstrate that early initiation of treatment may not necessarily be the optimal strategy for curtailing the incidence of resistance or the overall disease burden. The risk of developing drug-resistance in-host remains an important factor in the management of resistance in the population.
Networks (CT17)

Discussion leader: István Z. Kiss

Multi-node Basin Stability in Complex Dynamical Networks

Chiranjit Mitra$^{1,2}$, Anshul Choudhary$^{3,4}$, Sudeshna Sinha$^3$, Jürgen Kurths$^{1,2,5,6}$, and Reik V. Donner$^1$

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Dynamical entities interacting with each other on complex networks often exhibit multistability. The stability of a desired steady regime (e.g., a synchronized state) to large perturbations is critical in the operation of many real-world networked dynamical systems such as ecosystems, power grids, the human brain, etc. This necessitates the development of appropriate quantifiers of stability of multiple stable states of such systems. Motivated by the concept of basin stability (BS) [P. J. Menck et al., Nat. Phys. 9, 89 (2013)], we propose here the general framework of multi-node basin stability for gauging global stability and robustness of networked dynamical systems in response to non-local perturbations simultaneously affecting multiple nodes of a system. The framework of multi-node BS provides an estimate of the critical number of nodes which when simultaneously perturbed, significantly reduces the capacity of the system to return to the desired stable state. Further, this methodology can be applied to estimate the minimum number of nodes of the network to be controlled or safeguarded from external perturbations to ensure proper operation of the system. Multi-node BS can also be utilized for probing the influence of spatially localized perturbations or targeted attacks to specific parts of a network. We demonstrate the potential of multi-node BS in assessing the stability of the synchronized state in a deterministic scale-free network of Rössler oscillators and a conceptual model of the power grid of the United Kingdom with second-order Kuramoto-type nodal dynamics.

References

Bistability, Rate Oscillations and Slow Rate Fluctuations in a Neural Network with Noise and Coupling Delays

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A network of randomly coupled rate-based neurons influenced with different sources of noise and coupling delays is studied. A second-order stochastic mean-field model for the network dynamics is derived. This model is used to analyze the system dynamics and bifurcations in the thermodynamic limit, as well as to study the fluctuations due to the finite-size effect. Different types of noise, the internal and the external ones, were shown to have substantially different impact on the network dynamics. Although the both sources of noise give rise to stochastic fluctuations, only the external one affects the mean activity levels of the network.

In a wide interval of parameters the bistable dynamics of the network was observed with two different stable levels of activity coexisting. The origin of the bistability is related to the pitch-fork bifurcation. In the presence of coupling delays, the stationary levels may destabilize via Hopf bifurcations giving rise to stable oscillations of the mean rate. In the vicinity of the pitch-fork bifurcation, the noise-induced slow stochastic fluctuations of the mean rate were obtained. Their mechanism was shown to be associated to noise-induced transitions in a double-well potential. The developed mean-field model correctly predicts the parameter regions and the characteristics of the observed complex dynamical regimes.

References

Symmetry Breaking in a Ring of Coupled Cells with Glycolytic Oscillatory Reaction

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Our experimental work is focused on observation of transitions among discrete nonuniform stationary states (discrete Turing patterns) and different oscillatory regimes in a cyclic array of coupled cells with glycolytic oscillatory reaction. Cells utilize yeast extract as a source of fresh enzymes of glycolytic reaction chain and D-glucose solution as a substrate for glycolysis. Two main cells represented by quartz cuvettes are coupled by reciprocal peristaltic pumping, where each coupling capillary represents a cascade of continuous stirred tank reactors (cells). The residence time in coupling capillaries serves as an approximation of length of a cascade of cells between two main cells, which simulates the time delay coupling patterns observed in models of neural networks 1,2,3.

Dynamic regime of each main cell is measured by UV-Vis spectrophotometer focused on concentration levels of two phosphorylation connected metabolic pools, namely adenosine pool and nicotinamide adenine dinucleotide pool, specifically 260nm for ATP, ADP, AMP, NAD+ and 340nm for NADH.

By application of carefully chosen perturbations of main cells using ATP, AMP, D-glucose and yeast extract, we aim to use the system as a chemical computing unit working either as a neural network system with time delay coupling, or as a logic XOR gate, based on spatial distribution of measured nonuniform stationary states.

References

Control of Synchronization in Complex Oscillator Networks Via Time-delayed Feedback

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Synchronization as a phenomenon arises in various artificial and natural systems. The coherent behavior of coupled oscillators can be observed in many cases, e.g. coupled Josephson junctions, chemical reactions, cardiac pacemaker cells, flashing of fireflies, neurons in the brain, and power grids. The synchronous behavior can be desirable or harmful. The ability to control synchrony in oscillatory networks covers a wide range of real-world applications, starting from neurological treatment of Parkinson’s disease to the design of robust power grids.

Phase reduction is a powerful theoretical technique to analyze an appearance of synchronization in weakly coupled oscillator networks, since it allows the approximation of complex high-dimensional dynamics of oscillator with a single phase variable. A coupling strength and dissimilarity of frequencies are the main factors determining the synchrony in the phase model of coupled oscillators. The ability to change these parameters will easily allow to control synchronization in networks. However in typical situation, the phase variable is not attained for direct measurements and actions. Instead of this, one has an access to dynamical variables of the oscillators.

In this work we treat the oscillators of the network as black-boxes containing single-input single-output. We consider control signal $u(t)$ consists as a difference of the present and delayed output signals $s(t) - s(t - \tau)$ amplified by some factor $K$, where the delay $\tau$ close to the natural period of the controlled oscillator $T$. By employing phase reduction for systems with the time-delay [1] we derive the phase model of the network [2]. It fully coincides with the phase model of the uncontrolled network, the only difference being that the coupling strengths and frequencies depend on the control parameters $K$ and $\Delta T = \tau - T$. Surprisingly, the obtained analytical relations are almost universal, i.e. they neither depend on the coupling interoscillatory function, nor on the network topology, and the dependence on the particular model of the limit cycle oscillator comes through a single constant. The coupling strengths have a multiplicative inverse dependence on the feedback control gain. Thus, by appropriate choice of $K$, the coupling strength can be selected from zero to infinity. As a consequence, the synchronization can be achieved even if the oscillators are almost uncoupled. The analytical results are verified numerically on networks of diffusively coupled Stuart–Landau and FitzHugh–Nagumo models.

References

Fluctuations and Stability of Emergent Hierarchies in Social Systems

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Hierarchy is a near-ubiquitous property of social organization observed in societies ranging from insects to primates and humans. It has a profound effect on resource allocation, collective decisions and social stability [1,2]. Experimental evidence shows that both intrinsic abilities of individuals and self-reinforcement through interaction play a crucial role in the emergence and maintenance of hierarchy [3]. Yet, analytic studies of emergence have focused on the role of self-reinforcement, for example the influential work of Bonabeau et. al. introduced a minimal model describing a process that allows initially equal agents to form a stable hierarchy [4]. In the model, each agent is described by a score that determines their ability to dominate others. Two processes affect this score: (i) the agents participate in pairwise competitions, after which the score of the winner increases, and (ii) the score of each agent decays exponentially over time. Using a meanfield approximation, it was shown that for large decay rates egalitarian society is stable, and decreasing the decay rate leads to the emergence of a hierarchy through a series of bifurcations [5].

Here, rather than the meanfield approximation, we derive and solve the Fokker-Planck equations governing the evolution of the score distribution. This allows us to study stochastic phenomena observed in the hierarchical phase such as rank switching, mixing time and score fluctuations. We also generalize the model to take into account intrinsic abilities of the agents. We identify parameter regimes where the emergence of hierarchy is dominated by either social reinforcement or intrinsic ability. We study the systems response to external perturbations, such as removal or addition of an agent focusing on the relation between social ranking and ranks based on intrinsic abilities.

References

The emergence of spontaneous synchronization in asymmetric complex networks is a paradigmatic dynamical behavior nowadays. Recently, Nishikawa and Motter [1] put forward a rather intriguing network dynamical phenomenon: the asymmetry-induced symmetry, a scenario where dynamical uniformity and consensus do require the asymmetry of the underlying network. In many senses, this new phenomenon can be interpreted as the converse of the well known symmetry breaking process, for which the dynamical behavior or solution of a given system does not inherit all its symmetries. Despite its unequivocal interest from a more fundamental point of view, the asymmetry-induced symmetry has a wide range of possible applications, particularly in synchronization problems, where the new phenomenon was indeed discovered. We report here some new results which could be classified also as asymmetry-induced symmetry. Differently from [1], we consider spontaneous synchronization in large scale random networks. By exploring some recently proposed ideas and algorithms on optimal synchronization [2], we show that an excess of symmetries in the network tends to diminish its synchronization capacities or, in other words, asymmetry enhances synchronization, in the same spirit of Nishikawa and Motter new phenomenon. We consider the Stuart-Landau (SL) model with complex oscillators for an $N$-nodes network

$$\dot{z}_k = (\alpha^2 + i\omega_k - |z_k|^2) z_k + \lambda \sum_{j=1}^{N} a_{kj} (z_j - z_k),$$

where $z_k$ is the state of the oscillator located at the $k$ node, with $\omega_k$ standing for its natural frequency, which we assume to be a random variables. The matrix $a_{kj}$ is the usual adjacency matrix for undirected and unweighted networks, and $\lambda$ defines the (uniform) coupling strength between the oscillators. The parameter $\alpha$ determines the stability properties of the limit cycle $|z_k|^2 = \alpha$, which is present for $\lambda = 0$. For larger values of $\alpha$ (compared with $\lambda$), one recovers the paradigmatic Kuramoto model. For our purposes, a convenient description for the global state of the SL model is given the phases order parameter defined

$$r = \left| \frac{1}{N} \sum_{j=1}^{N} e^{i \arg z_j} \right|.$$

The behavior of $r$ for the SL model is analogous to the Kuramoto case: $r \approx N^{-1/2}$ for incoherent motion, whereas $r \approx 1$ for a fully synchronized state. Starting from bilayer random networks with many symmetries, we show that the optimization algorithm introduced in [2] typically will break the network symmetries to improve its synchronization capacity. We will present some statistical evidences of this asymmetry-induced enhancement of synchronization and discuss some possible applications [3].

References


The Role of Attractors in the Closed-loop Scheme of Robotic Locomotion

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General robotic locomotion aims to endow robots with the ability to navigate in and to interact with complex environments. To achieve this, the robot has to take into account the feedback of the external world, incorporating it in a closed-loop control scheme for generating self-organized, rather than top-down controlled locomotion [1].

Following the recently emerged dynamical systems approach to robotics, also termed as robophysics [2], we investigate the sensorimotor loop of rolling robots within the LPZRobots simulation environment [1]. The considered cylindrical and sphere-shaped robots contain one, respectively three internal weights, each of them moving along a separate rod. The dynamics of individual weights is modulated by single neurons via measuring their actual position and computing new target positions. In turn, the activity of neurons is regulated by internal, and synaptic plasticity effects, respectively. The wide palette of motion patterns is, hence, generated through the interaction of the internal control mechanisms and the environment through the induced forces.

We present a new approach to the study and generation of motion primitives in terms of attractors in the overarching phase space of the robots internal variables and of the environment it is situated in. Hence, embodiment can be characterized as the generation of self-organized limit cycle behavior resulting from the additional degrees of freedom of the external phase space [3]. We argue that the online interaction with the surrounding environment is of crucial importance, since it allows for an autonomous switching of locomotion modes via visiting other attractors, or even by the transient use of otherwise non-attracting relicts in the phase phase [4]. Since all the here discussed attractors have a continuous degeneracy in the plane of physical coordinates, the partially predictable chaotic mode [5] can be seen as a realization of smooth chaotic wandering.

References

The bifurcation structure of periodic solutions of a harmonically driven asymmetric nonlinear oscillator (Rayleigh-Plesset equation, describing bubble dynamics) is examined. The control parameters were the amplitude and frequency of the driving with frequency values higher than the subharmonic resonance frequency of the system. In the investigated parameter region, the endoskeleton of the bifurcation structure, composed by solutions with low periodicities, can be described by an asymmetric Farey-ordering tree. To each periodic domain, a sub-structure can be associated created by period-$n$ tupling processes, whose topology are governed by a two-sided symmetric Farey tree. Higher order sub-structures apparently exhibit self-similar features.

The extensive study of harmonically driven nonlinear oscillators has revealed several topological universalities in the last few decades with respect to a single control parameter. For instance, the standard Feigenbaum period doubling cascades or the alteration of periodic and chaotic windows via crises [1]. The topological description in two or more dimensional parameter space, however, is less elaborated. The present investigation intends to extend our knowledge on bi-parametric bifurcation structure in the amplitude-frequency parameter plane of the driving via thorough numerical analysis.

The mathematical model describing the radial oscillation of a single spherical gas bubble in water (Rayleigh-Plesset equation [2]) can be written as

$$\frac{d^2 R}{dt^2} + \frac{3}{2} \frac{dR}{dt} = \frac{1}{\rho_L} \left( p_G + p_V - \frac{2\sigma}{R} - 4\mu_L \frac{dR}{dt} - P_\infty - p_A \sin(\omega t) \right),$$

where $R(t)$ is the time dependent bubble radius, $\rho_L = 997.1$ kg/m$^3$ is the liquid density, $p_G$ is the gas pressure inside the bubble following a simple polytropic state of change, $p_V = 3166.8$ Pa is the vapour pressure, $\sigma = 0.072$ N/m is the surface tension, $\mu_L = 8.9024$ Pa s is the viscosity, $P_\infty = 5458$ Pa is the ambient pressure, $p_A$ is the amplitude and $\omega$ is the frequency of the driving.

Figure 1: First component of the Poincaré section of the dimensionless bubble radius as a function of the pressure amplitude.

Figure 1 shows the bifurcation structure of the periodic solutions as a function of the pressure amplitude $p_A$ at frequency approximately 3 times the linear eigenfrequency. The bold fractions denote the winding numbers [3] of the saddle-node bifurcations of the corresponding periodic windows. The main periodic
structure is governed by a winding number sequence 1/2, 1/3, ..., 1/9 with an increment of 0/1 constituting an asymmetric Farey tree. The sub-structures associated to each main periodic windows, however, form a double sided Farey tree. For instance, in case of the periodic domain of order 1/3 (see the left hand side of Fig. 1): 2/7, 3/10, ... 1/3 ..., 5/18, 4/15, 3/12, 2/9. The increment is exactly 1/3 from both sides. According to more detailed simulations, the higher order sub-structures show the same double-sided topological behavior.

Acknowledgment

This paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences.

References

Reservoir Computing Beyond Memory-Nonlinearity Trade-off

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Reservoir computing is a brain-inspired method of information processing, and implementations of reservoir computing by employing a various types of dynamical systems are being extensively studied [1]. In this talk, we give a theoretical explanation of the memory-nonlinearity trade-off, which is a key property of the working principle in reservoir computing. Moreover, based on the memory-nonlinearity trade-off, we propose a novel reservoir structure that we call a mixture reservoir and show that it improves the performance of the information processing remarkably.

References

Characterizing Rare Fluctuations in Soft Particulate Flows

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Soft particulate media include a wide range of systems involving athermal dissipative particles both in non-living and biological materials. Characterization of flows of particulate media is of great practical and theoretical importance. A fascinating feature of these systems is the existence of a critical rigidity transition in the dense regime dominated by highly intermittent fluctuations that severely affects the flow properties. Here, we unveil the underlying mechanisms of rare fluctuations in soft particulate flows. These fluctuations have different origins above and below the critical jamming density and become suppressed near the jamming transition. We establish a time-independent local Fluctuation Relation, which we verify numerically, and use it to introduce an effective temperature for dense particular flows. Similarities and differences between the proposed effective temperature and the widely used kinetic temperature are discussed by means of a universal scaling collapse.

Acknowledgment

Lyapunov Analysis of Chaotic Itinerancy in FORCE-based Neural Network Learning

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Recently, the paradigm known by the name of reservoir computing (RC) has attracted much attention as a new way of recurrent neural network (RNN) learning to display various information processing functions [1]. Especially, Sussillo and Abbott proposed a version of RC, called FORCE-learning [2] (Fig. 1), and they showed how chaotic activity in a RNN is useful for generating various temporal patterns.

In this study, we employ a FORCE-learning to generate multiple temporal patterns initiated by the combination of trigger pulses ("attention") through multiple channels. We show that such a RNN-based pattern generator is actually constructed, whose performance is maximized in a parameter region where the trained RNN exhibits chaotic behavior with some "pliable" property. Furthermore, when there are no trigger inputs (spontaneous mode), intermittent transitions among several typical patterns appears, which reminds us chaotic itinerancy (Fig. 2)[3]. In this study, we characterize such a pliability of chaos in terms of Lyapunov analysis and discuss the background mechanism of our observations.

Acknowledgment

This study is supported by MEXT/JSPS KAKENHI Grant Number 16H01617, 25120011 and 16K00059.

References

Quantum Dynamical and Topological Manifestations of Superweak Chaos

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This talk is a brief review of quantum dynamical and topological properties of the system of charged particles periodically kicked by a periodic potential $V(x)$ perpendicularly to a uniform magnetic field [1-7]. This system is a paradigm of Quantum Chaos and exact special cases of it are the kicked Harper models [2,4]. A general approach to the system [2-7] takes into account all the values of a constant of the motion, the $x$ coordinate $x_c$ of the cyclotron-orbit center. In fact, all these values appear in a generic ensemble of particles and the classical and quantum properties are very sensitive to $x_c$. In particular, for some $x_c = x_c^*$ and for small kick strength $\kappa$, the system behaves as if this strength is effectively $\kappa^2$ [2,6,7]. This implies, e.g., a chaotic diffusion much slower than the already slow one for other $x_c$ values. This phenomenon, which we call "superweak chaos" (SWC), was first observed [2] as a classical fingerprint of quantum antiresonance (flat quasienergy (QE) band). The classical (quantum) transition $x_c \rightarrow x_c^*$ was later studied in work [6] (work [7]). For rational values of a scaled Planck constant, the QE bands can be characterized by topological Chern integers satisfying a Diophantine equation [8], analogous to the one for the quantum Hall effect [9]. Then, the transition $x_c \rightarrow x_c^*$ turns out to be, quantally, a topological phase transition. SWC emerges under much more generic conditions in "kicked Hall systems" [10], i.e., the system above with the addition of a uniform electric field perpendicular to both the kicking direction ($x$) and the magnetic field. The quantum dynamical and topological manifestations of this generic SWC are currently under investigation [11].

References

Noise Effect on the New Theory of Intermittency

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Intermittency is a specific route to the deterministic chaos when spontaneous transitions between laminar and chaotic dynamics occur. The concept of intermittency has been introduced by Pomeau and Manneville [1-3]. Later it has been found that transition to chaos through intermittency occurs in periodically forced nonlinear oscillators, Rayleigh-Bénard convection, derivative nonlinear Schrödinger equation, turbulence evolution in hydrodynamics, plasma physics, neuroscience and economic. According to the type of instability in the laminar phase, the intermittency phenomena are usually classified in three classes called I, II, and III.

The main attribute of intermittency is a global reinjection mechanism that maps trajectories of the system from the chaotic region back into the local laminar phase. This mechanism can be described by the corresponding reinjection probability density (RPD). The RPD is a fundamental property of intermittency, determined by the chaotic dynamics of the system. Correct characterization of intermittency allows us to study problems with partially known governing equations as it happens in medicine and economics. As analytical expressions for the RPD are available for a few problems only, the most common approximation used to obtain many classical results on intermittency theory have been considered the RPD uniform, that is independent of the reinjection point (see for instance [3-4]).

Recently a generalization of the classical intermittency theory has been presented, where new methods to investigate the RPD in systems showing Type-I, II, or III intermittency are offered. The classical theory is included in this new framework as a particular case. We generalize the classical analytical expressions for the RPD providing new laminar lengths and new characteristic relations in good agreement with experimental or numerical data [5-9]. The interested reader on this topic is referred to reference [10].

Noise may have strong impact on the intermittency phenomena. The generalized RPD introduces a novel scenario, because, whereas the uniform reinjection should remain constant under a wide class of noise distributions, the new one is affected by the noise. Recently an analytical approach to the noisy reinjection probability density (NRPD) has been presented [11-13].

Here, we present an experimental system based on an analog electronic circuit having intermittency. We are focusing on the role of the noise in the system and we found good agreement with the new noisy intermittency approach. It is also important to note that a complete description of the ideal noiseless system and the real noisy experiment can be obtained from experimental noisy data.

Acknowledgment

This work was supported by the former Spanish Ministry of Science and Innovation (ESP2013-41078-R), by CONICET, National University of Córdoba, MCyT of Córdoba and the Polytechnic University of Madrid (UPM).

References


Physical Aging and Emerging Long-period Orbits in Deterministic Classical Oscillators

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We identify physical aging in a deterministic system of repulsively coupled Kuramoto oscillators, which are exposed to a fixed distribution of natural frequencies. Physical aging is understood as the breaking of time translation invariance in the measurement of autocorrelation functions and long intrinsic time scales. Tracing back the origin of aging, we identify the long transients that it takes the deterministic trajectories to find their stationary orbits in the rich attractor space. The stationary orbits show a variety of different periods, which can be orders of magnitude longer than the periods of individual oscillators. The smaller the width of the distribution about the common natural frequency is, the longer are the emerging time scales on average. Among the long-period orbits we find self-similar temporal sequences of temporary patterns of phase-locked motion on different time scales. The ratio of time scales is determined by the ratio of widths of the distributions. The effects are particularly pronounced if we perturb about a situation in which a self-organized Watanabe-Strogatz phenomenon is known to happen, going along with a continuum of attractors and a conserved quantity.

References

Optimal Entrainment of the Spikes Emitted by a Semiconductor Laser with Feedback

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The nonlinear dynamics of a semiconductor laser induced by optical feedback has been intensively studied in the last three decades, not only because these lasers are important practical devices, but also, because of the wide range of complex regimes that can be induced by optical feedback. The chaotic optical output generated has found various applications (secure communications, information processing, LIDAR, random number generation, etc.). In this contribution we focus on a dynamical regime known as low frequency fluctuations (LFFs), in which the laser emits an spiking output with dynamical properties that resemble the spike sequences of biological neurons. Operating in this dynamical regime, semiconductor lasers can be building blocks of ultra-fast information processing systems inspired in the way biological neurons process information. To use the laser as an information processing unit, it is crucial to understand how the information of a weak input signal is encoded in the output sequence of optical spikes.

In this contribution we consider the simplest situation of a weak periodic signal which is applied to the laser via direct current modulation. We present an experimental study of the role of the signal waveform and laser operation conditions in the entrainment of the output spikes to the periodic input. We propose several measures to quantify entrainment (inter-spike-interval distribution, spike success rate and ordinal spike correlations [1] [2]) and use them to analyze which waveform (at a given mean value and oscillation amplitude) produces optimal entrainment.

Figure 1 displays the ISI distributions for a semiconductor laser subject to an optical feedback and an external current modulation. Two periodic waveforms have been used. In Figure 1a we show the ISI distribution when a pulsed signal is applied while in Figure 1b illustrates the ISI distribution under a sinusoidal waveform. In both cases, four different modulation frequencies are chosen to show up the first four locking scenarios displayed by the dynamical system.

In the case of pulsed modulation, locking 1:1, 2:1, 3:1 and 4:1 (revealed by a high and narrow peak in the ISI distribution at $n \cdot T_{mod}$) are observed at modulation frequencies $f_{mod} = 7, 14, 25$ and 35 MHz respectively. On the other hand, for the sinusoidal test, a much broader ISI distributions are observed at low modulation frequencies which reveals an heterogeneous distribution of the power dropouts (i.e. poor entrainment). At higher frequencies the ISI distribution becomes narrower and the dynamical response of the system approaches to the one observed with the pulsed modulation. Therefore, our results indicate that, for entraining the power dropouts, the pulsed waveform is more efficient than the sinusoidal
waveform.

**Acknowledgment**

This work was supported in part by European Commission through the FP7 Marie Curie Initial Training Network NETT (289146), Spanish MINECO/FEDER (FIS2015-66503-C3-2-P) and ICREA ACADEMIA, Generalitat de Catalunya.

**References**


High Efficient THz Wave Detections Using Metal V-grooved Waveguide(MVG) and Generations Using Laser Chaos

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Generation of a stable wide-range THz Wave using a chaotic oscillation in a multimode semiconductor laser with an optical delayed feedback by the external mirror is investigated. A mode-locked Ti:sapphire laser is frequently used to excite the Voltage-biased photoconductive antenna (PA). But it is a high cost system. A multimode semiconductor laser is also used to excite the antenna ¹,²). This system is low cost but a spectrum of generated THz wave is essentially line spectrum with a frequency interval between longitudinal modes of a semiconductor laser. And also time series of THz wave is not stable since mode hopping in multimode semiconductor lasers suddenly occurs.

We propose to use a chaotic oscillation of a semiconductor laser in order to obtain stable low cost continuously wide range THz wave. And a Metal V grooved Wave guide (MVG) is also used to detect the THz waves effectively. In this paper we investigate the dependence of the MVG gap width on the THz signals.

Acknowledgment

This research and development work partially supported by the Collaborative Research Based on Industrial Demand from Japan Science and Technology Agency, JST. Project name: Development of Super Sensitive Electro-Optics Sampling Scheme for Terahertz Waves and the MIC/SCOPE # 165005001.

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Environmental Systems (CT20)

Discussion leader: Annette F. Taylor

The Effect of Climate Change on the Topological Entropy of Atmospheric Pollutant Clouds

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Our research addresses the question how a changing climate influences the spread of pollutants on continental and global scale. For characterizing the spread a measure of chaotic systems, namely, the topological entropy, is used. This quantity describes the exponential stretching of pollutant clouds, and therefore, it is related to the predictability and the complexity of the structure of a pollutant cloud. For the dispersion simulations meteorological reanalysis data are utilized from 1979 to 2015. Our simulations demonstrate that during this period the mean topological entropy slightly increased, resulting in that the length of a line-like pollutant cloud being advected for 10 days (30 days) in the atmosphere becomes 20–65% (200–400%) longer by the 2010s than in the 1980s. As a further aspect relationships between the time evolution of the stretching rate and different meteorological variables are analyzed. The mean topological entropy is found to be correlated with the mean absolute vorticity for given geographical regions and seems to be linked to the mean temperature.
Noise-induced Rare Events in Granular Media: a Volcanic-like Explosion

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Granular matter is ubiquitous in nature and exhibits a variety of nontrivial phenomena. Within the same system, different regions of granular media can be at a solid or a gas phase. Here we focus on a granular Leidenfrost effect: a solid-like cluster is levitating above the "hot" granular gas [1]. This state was observed experimentally, when granular matter was vertically vibrated in a two-dimensional container [2]. The solid-gas coexistence can be described by using granular hydrodynamics, taking into account the viscosity divergence in the solid cluster. The approach is similar to the one employed in investigating solid-fluid coexistence in dense shear granular flows [3]. We performed extensive molecular dynamics simulations of a simple model of inelastic hard spheres driven by a "thermal" bottom wall. Simulations showed that for low wall temperatures, the levitating cluster is stable, while for high wall temperatures, it breaks down, and a hot gas bursts out resembling a volcanic explosion [4]. We found a hysteresis: for a wide range of bottom wall temperatures, both the clustering state and the volcanic state are stable. However, even if the system is at the (stable) clustering state, a volcanic explosion is possible: it is a rare event driven by large fluctuations. We used techniques from the theory of rare events to compute the mean time for cluster breaking to occur; this required the introduction of a two-component reaction coordinate [4].

References

Recurrence Time Analysis in Exoplanetary Dynamics

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Parallel to the increasing number and variety of extrasolar planetary systems various methods have been proposed to describe and characterize either the short or long-time dynamics of these systems. Although, the methods introduced are fairly different in nature, one of the essential properties is common, namely, they are based on observational data sets and their uncertainties. Moreover, most of these methods use (direct or inverse) analytic, semi-analytic, or numerical computations in order to investigate the system’s stability and physical parameters. Reconstructing the dynamics from short and nonuniform noisy time series is a challenging task, especially without any direct orbital integration. In this work we propose a method of non-linear time series analysis and recurrence quantifications based only on collected data in order to quantify the dynamics of multi-planetary systems. Despite these methods are rarely used in high dimensional systems such as dynamical astronomy, carefully taken conditions might serve suitable description the orbital stability. The advantages and disadvantages of the method will also be discussed.
A Biophysical Network Model for Antisaccade Eye Movements

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We address a biophysical network model that is used to study the effects of dopamine on the performance of subjects with schizophrenia during an antisaccade task and compare the differences in functional connectivity in the prefrontal cortex (PFC) as compared to the controls. The values of the biophysical parameters of the model, i.e. the values of the conductances of the ionic currents, reflecting the level of dopamine, as well as the structure of the functional network connectivity in the PFC were computed by wrapping around the simulator an optimization algorithm that minimized the differences between simulations and experimental behavioral data. Our results show that the model approximates remarkably well the effects of dopamine modulation on the distribution of the antisaccade reaction times (aSRT), as well as the changes of the connectivity in the PFC that have been observed in neuroimaging studies.
The Interplay of Synchronization in Epilepsy and Sleep: A Data-driven Approach

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Application of time series analysis techniques to biomedical data is key to a better understanding of many dynamics derived from complex physiological and pathological processes. In particular, applying these techniques to electroencephalographic recordings (EEG) can provide us with an advanced characterization of the underlying brain dynamics. In epilepsy, these dynamics are altered as result of a disturbed coordination between neuronal populations. It is known that these disturbances lead to abnormal hypersynchronization and hypo-synchronization of neuronal activity. Furthermore, physiological processes such as sleep have a strong impact on synchronization of brain dynamics. The aim of this study is therefore to investigate the interplay of these phenomena from a data-driven point of view. For this purpose we analyze all-night recordings from epilepsy patients implanted with intracranial electrodes. We use linear and non-linear time series analysis techniques to assess the synchronization patterns from these recordings. Our objective is to characterize the epileptic activity during sleep to investigate whether this type of analysis can contribute to the localization of the seizure onset zone, the brain region from which initial seizure discharges can be recorded.
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50. Harshini Tekur, "Spacing Distribution of Localized States and Their Nearest Neighbours in Quantum Chaos"

51. Matt Tranter, "Scattering of Bulk Strain Solitons in Layered Structures"

52. Ágota Tóth, "Flow-driven Morphology Control in Transition Metal-oxalate Systems"

53. László Valkai, "Stochastic Kinetics or Imperfect Mixing Driven Irreproducibility?"

54. Hendrik Wernecke, "Binary Test for Partially Predictable Chaos"

55. Hendrik Wernecke, "Target Points in Neural Dynamics"

56. Dirk Witthaut, "Quantum Signatures of Synchronization"
1. Front Propagation Into Unstable States In Discrete Media

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Macroscopic systems under the influence of injection and dissipation energy, momenta, or matter often exhibit coexistence of different states. Inhomogeneous initial conditions, usually caused by inherent fluctuations, generate domains that are separated by their respective interfaces. These interfaces are known as front solutions, domain walls or wave fronts depending on the physical context where they are considered [1].

We investigate front propagation into an unstable state in discrete media based on a paradigmatic model of populations dynamics known as Fisher-Kolmogorov-Petrosky-Piscounov model. We show that the front spreads in a pulsating manner for FKPP model [3, 4]. The mean speed of the front increases as the distance between the grid point increase, meanwhile different parts of the front propagate in an oscillating manner with the same frequency but different amplitude as we can see in Fig. 1.

![Figure 1: a) Spatiotemporal diagram for discrete FKPP equation. b) Speed of the front propagation as function of time for different dx (distance between two adjacent points of the grid)](image)

The asymptotic behavior of the front solution allows us to determine the minimum mean speed analytically of fronts as a function of the medium discreteness [2]. To describe this latter phenomenon, we generalize the notion of the Peierls-Nabarro potential, which allows us to have an effective continuous description of the discreteness effect. The shape of the oscillations is characterized numerically showing quite good agreement between the discrete medium and the effective continuous system.

References

2. Explosive Synchronization in Dynamically Frustrated Systems

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One of the most significant challenges of present-day research is bringing to light the processes underlying the spontaneous organization of networked dynamical units. Discontinuous transitions to synchronized states of networked phase oscillators were initially reported in a Kuramoto model for a particular frequency distribution and network topology [1]. The same finding was also described for both periodic [2] and chaotic [3] phase oscillators in the yet particular condition of a heterogeneous degree-distribution with positive correlations between the node degree and the corresponding oscillator’s natural frequency. Later on, it was shown that explosive synchronization can be obtained for any given frequency distribution, provided the connection network is constructed following a rule of frequency disassortativity [4, 5].

These studies so far have concentrated on proposing topologies for which the transition is explosive, given a specific frequency distribution on the dynamical units, or vice versa, proposing a frequency distribution on the oscillators, given a specific connectivity structure. However, no models have yet succeeded in generating dynamically the conditions for a transition to be explosive. We show here that these conditions may spontaneously emerge in an adaptive network of interacting oscillators, as the result of a delicate interplay between synchronization processes and co-evolution of the connectivity structure. When the connectivity dynamics is such that links coupling the nodes with non-synchronous (synchronous) dynamics are promoted (weakened), we prove that an initially unstructured clique configuration evolves in time toward an emerging structured network whose transition is explosive. We also study the parameter space of this model to demarcate the region in which this happens.

References

3. Marangoni Instability in a Propagating Autocatalytic Reaction Front Under Microgravity

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The oxidation of arsenous acid by iodate ions is an autocatalytic reaction in which the interplay between diffusion and the reaction itself leads to a propagating reaction front. In the course of the reaction the physical parameters of the fluid change. When the reaction is run in the presence of a gas-liquid interface, gradients in density and surface tension are generated which may lead to natural convection[1]. The role of Marangoni-related flow in the characteristics of this propagating autocatalytic front has been studied on board of the MASER-13 sounding rocket. The rocket mission has allowed approximately six minutes of microgravity (compared to 20 s in parabolic flights[2]) which is sufficient to examine the Marangoni effect alone by excluding any buoyancy related flows ever present in normal gravitational conditions. The experiments have been performed in two different-sized quartz cells with a liquid-gas interface. The mixture has contained latex beads with a mean particle size of 6.4 µm for Particle Image Velocimetry (PIV). The geometry and the propagation of the front have been monitored using Fourier deflectometry, while three laser sheets in each cell have allowed the detection of the fluid flow field by PIV. Numerical simulations are also performed by solving the Navier-Stokes equation by applying the pressure implicit with splitting of operators algorithm using the OpenFOAM package. By modeling the reaction-diffusion-advection system driven by the Marangoni-flow, we are able to reproduce the flow conditions which have been observed during the experiments in microgravity.

Acknowledgment

Financial support by ESA (4000102255/11/NL/KML) is gratefully acknowledged.

References

4. Recurrence Plot Analysis of Experimental Nonlinear Behaviors at the Nanoscale

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Environmental microscopy techniques allow probing the dynamics of catalytic systems down to the nanoscale. At this scale, the large fluctuations that are inherent to small chemical systems can endanger the regularity of dynamical behaviors. In this work, field emission techniques are used to probe the dynamics of two nanoscale catalytic systems (NO\textsubscript{2}+H\textsubscript{2}/Pt and O\textsubscript{2}+H\textsubscript{2}/Rh). Several nonlinear behaviors, such as self-sustained periodic oscillations and bistability, have been observed and thoroughly characterized.

Recurrence Plot Analysis (RPA) is a widely used technique of signal analysis. It allows for the identification of hidden regular patterns in complex, nonlinear dynamical systems. In the case of experimental data and nanoscale systems, and thus in the presence of noise, it might be difficult to discern different dynamics by regular data treatment. In this study, RPA is used to discriminate between periodic oscillations and fluctuating bistable systems. As a proof of concept, experimental bistability is compared to simulations of a noisy bistable theoretical model to validate the treatment for nanoscale systems.

Some experimental time series have characteristics of a bistable system subjected to strong fluctuations, but nevertheless present some regularity as evidenced by spectral analyses. To unambiguously discern between the different classes of dynamics, RPA is performed on the experimental time series and compared to models for stochastic periodic oscillations and stochastic bistability, which reveals that the signal is oscillatory in nature. The study is extended to the analysis of bimodal oscillations. As a conclusion, recurrence plot analysis appears to be a powerful and visual tool to discern between different dynamical behaviors, even in the presence of fluctuations and for noisy experimental data.
5. Transition State Theory for Solvated Reactions: The LiCN Isomerization Reaction

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The accuracy of rate constants calculated using transition state theory depends crucially on the correct identification of the reactive trajectories that contribute to the rate. This is a difficult task in systems that are subject to the randomly fluctuating influence of a thermal bath. Stochastically time-dependent invariant manifolds in the phase space of the reactive system are a powerful tool to overcome this difficulty. We show how to construct these manifolds in systems with nonMarkovian friction and obtain an explicit expression for the rate of crossing an anharmonic potential barrier. The excellent performance of our method is illustrated with an application to a realistic model for LiNC$\rightleftharpoons$LiCN isomerization. The rates obtained from invariant manifolds are in good agreement with large scale all-atom numerical simulations.

References

6. Intermittent Chaos in Bray-Liebhafsky Reaction as a Function of Specific Flow Rate

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Intermittent chaotic oscillations are a complex dynamic state where transition between two qualitatively different dynamic states occurs randomly.\cite{1} This type of oscillations is often prescribed to the influence of external perturbations, however, this self-organized phenomenon is an inherent property of the system that is governed by the values of the applied control parameters.\cite{2,3}

Intermittent oscillations, obtained in our experiments, represent a dynamic state where periods of high-amplitude oscillations (bursts) chaotically alternate with quiescent periods with no or low-amplitude oscillations (gaps). The present investigations are devoted to the examination of intermittent dynamic states, obtained by specific flow rate changes, under open reactor conditions (CSTR), in famous inorganic oscillatory reaction well known as Bray-Liebhafsky (BL) oscillator.\cite{4,5}

In our recently published paper, where intermittent chaos was experimentally generated in BL reaction, in CSTR, under controlled temperature variations, it was demonstrated that number of burst packages per unit of time can be used as a measure of chaos of intermittent dynamic states because of its excellent correlation with the largest Lyapunov exponent.\cite{3} Also it was shown that the number of bursts per unit of time as a function of the specific flow rate corresponds to an asymmetrical distribution function.\cite{6}

In present investigation, in analogy with our previous investigations, we calculated the Lyapunov exponents of the experimentally obtained intermittent dynamic states in BL system under specific flow rate variations. It was obtained that Lyapunov exponents as a function of specific flow rate will follow similar form of distribution function like number of bursts per unit of time.

References

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7. Nonlinear Mapping in Simple Climate Model with Memory

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The nonlinearity in climate physics is investigated for the zero-dimensional energy equilibrium model of climate system; the model is transformed into a nonlinear mapping equation with memory on the basis of self-memorization principle, which is to establish and solve a difference-integral equation derived from a differential equation of system. The nonlinear mapping equation is

\[ T_{n+1} = g(T_n - T_{n-1}) + h(T_n - T_{n}^{4}) + k \]

where \( T \) is temperature of climate system, \( g, h \) are coefficients relative to climate variables and memory characteristics, \( k \) is constant. Computation for the mapping equation results in some nonlinear phenomena in the zero-dimensional climate system. Periodic and chaotic variations of the system, depending on the thermal capacity and the memory of the system, have been revealed. Our study is conducive to understand the observed climate change, for example, global warming, long-term climate trend etc.

Acknowledgment

This work is supported by the National Natural Science Foundation of China under the grant 41375079.

References

8. Towards the Understanding of Evaporation Induced Pattern Formation of Decanol Droplets

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Pattern formation in far from equilibrium systems is observed in several disciplines including biology and reaction-diffusion chemistry, comprising both living and non-living systems. We aim to study such non-equilibrium dynamics of a novel system based on a 1-decanol droplet placed in a solution of alkaline decanoate. Recently, we have found that when the system is open to the environment and the evaporation of water from decanoate solution occurs we observe dramatic morphological changes of the decanol droplet. Moreover in the presence of sodium chloride it shows a novel type of pattern formation, namely the formation of long tentacular structures. We aim to analyze these structures at both the macroscopic and microscopic scale across a large range of initial conditions. Such reproducible morphological changes in simple droplets open a path for exploration of shape-based effects in larger scale pattern formation studies.

References

9. Interaction of Scroll Waves in an Excitable Medium: Reconnection and Repulsion

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Scroll waves are 3D counterparts of spiral waves that rotate around a one-dimensional space curves, known as its filament. Their presence in the cardiac tissues is many times the cause of arrhythmia that finally leads to heart failure. Interaction of scroll waves may have far-reaching consequences on cardiac activity. In fluids and liquid crystals, there is evidence of vortex interaction leading to interesting phenomena like filament reconnection. If likewise, scroll rings interact and reconnect, then small rings may merge and form large ones that will have enhanced life-times.

Here, we report the first experimental evidence of scroll wave reconnection in Belousov-Zhabotinsky reaction. Our results demonstrate that when two scroll rings are brought close enough, they can either attract each other, and reconnect to form a large scroll ring, or they can repel so that they rupture on touching the boundaries. We also carry out simple numerical simulations using Barkley model that helps explain the filament behavior in our experiments.

![Figure 1: Schematic diagram for scroll interaction.](image)

References

10. Reservoir Computing on an Active Silicon Photonics Chip Using Nonlinear Microrings Resonators

Florian Denis-le Coarer\textsuperscript{1,2}, Damien Rontani\textsuperscript{1,2}, Andrew Katumba\textsuperscript{3}, Matthias Freiberger\textsuperscript{3}, Joni Dambre\textsuperscript{3}, Peter Bienstman\textsuperscript{3}, and Marc Sciamanna\textsuperscript{1,2}

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The vast amount of data collected every day requires new paradigms for high-speed, energy efficient, information processing techniques. These challenges are addressed through the implementation of machine learning technique at the physical layer. Among the existing techniques, the implementation of reservoir computing on various hardware platforms, included photonics [1, 2], seems to be a very promising candidate for processing real-time data in optical fiber networks with rates exceeding 10 Gb/s.

We present here a novel architecture depicted in Fig. 1(a). The design is similar to an existed chip presented by Vandoorne \textit{et al.} [1], where we replace the passive nodes made of waveguides, splitters and combiners by nonlinear micro rings resonators [3]. Using numerical simulations, we demonstrate that a reservoir computer paradigm based on this type of integrated photonic chip can perform a typical XOR Boolean operation between two consecutive bits \((x[k-1] \oplus x[k])\) up to 20 Gb/s. Figure 1(b) shows the error rate for an increasing number of nodes of a reservoir computer with a swirl topology at two different bitrates : 10 Gb/s (black dots) and 20 Gb/s (red squares) for the typical XOR Boolean operation, trained using ridge-regression. Higher bitrates with similar - or better - performances are expected using larger networks based on micro-ring resonators.

Acknowledgment

F.D., D.R. and M.S. acknowledge the support of the fondation Supélec, Préfecture de Région Grand-Est, Région Grand-Est, Metz Métropole, Département de la Moselle, AIRBUS GDI Simulation for the Chair in Photonics. This work is performed in the frame of the H2020 PHRESCO project. D.R acknowledge the AFSOR through grants FA9550-15-1-0279 and FA9550-17-1-0072.

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11. Non-inertial Mechanisms for Clustering of Settling Particles

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The density of settling particles accumulated on the bottom surface of an incompressible fluid often exhibits inhomogeneities (i.e., clustering), which is usually supposed to be related with inertial effects. Earlier work [1] has shown, however, that inertial effects are negligible in the parameter range of settling biogenic particles in relevant ocean flows, and that clustering nevertheless occurs for such particles. Here we describe the two different non-inertial mechanisms leading to clustering. One mechanism is dynamical: the density varies within sheets of dimension lower than that of the embedding fluid during the time evolution of these sheets, since incompressibility holds only for the full-dimension volume element. The other mechanism is a simple projection of the densities within such moving sheets onto the bottom surface. Clustering occurs when these sheets are inhomogeneously tilted with respect to the bottom surface, and their non-vertical velocity also needs to be taken into account during the projection. Foldings of the sheets and corresponding caustics play a special role. We systematically explore the relative importance of the two main mechanisms in numerical examples.

References

12. Reaction-Diffusion Patterns in Initially Separated Landolt-type pH Oscillators

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Laboratory of Nonlinear Chemical Dynamics, Institute of Chemistry, Eötvös Loránd University, Budapest, Hungary

Pattern formation in reaction-diffusion systems has been widely investigated owing to its theoretical and practical importance in geological and biological systems. It is known that the initial and boundary conditions determine the basic properties of the developing pattern. Now we study the reaction-diffusion system of the well-known Landolt-type pH oscillator [1] in a new setup, where the reactants are spatially separated at the beginning. [2] The general mechanism of the Landolt-type pH oscillators includes a H⁺-autocatalytic and a H⁺-consuming step. This reaction system shows bistability and oscillation in a continuously fed homogeneous medium, and results in traveling waves and stationary Turing patterns in a reaction-diffusion system where the concentrations are fixed at one of the boundaries. [1] In our setup the reaction-diffusion system is divided into two parts, which are filled homogeneously with different reactants at the initial moment (Fig. 1.). There is no external reagent supply.

The initially separated reactants start to diffuse due to the concentration gradients and the autocatalytic reaction between SO₃²⁻ and the oxidant can occur in the counter-diffusion zone. In our one-dimensional numerical simulations an acidic band appears in the middle, which is bounded with autocatalytic and diffusive fronts. The propagation of these fronts is limited by the H⁺-consuming reaction, therefore the width of the band is nearly constant. The direction of the front propagation can be tuned by the initial amount of the oxidant, because the initial [SO₃²⁻]/[Ox] ratio determines the concentration gradients and the location of the autocatalytic front. We studied the behavior of the acidic band in experiments as well and the observations are in good accordance with the model.

The most interesting simulated phenomenon is the damped oscillation at the beginning of the acidic band (Fig. 2.). When the local [HSO₃⁻] and [Ox] becomes high enough to start the autocatalytic process, the H⁺ ions accumulate (black needles). Then the H⁺-consuming step binds the H⁺ excess and the relatively high [SO₃²⁻] delays the new accumulation period. The periodic behavior cannot be sustained because there is no external source of SO₃²⁻, and its diffusive supply becomes slower in time. The existence of oscillation depends on the kinetic of the autocatalytic reaction (what is determined by the oxidant); this could be the reason why the experimental evidence of the predicted oscillation has not been found yet.

References

13. Global Bifurcations of Limit Cycles and Strange Attractors

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We study global bifurcations of limit cycles and strange attractors in low-dimensional polynomial dynamical systems. To control the global bifurcations of limit cycles in two-dimensional 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 stating that the maximal one-parameter family of multiple limit cycles terminates either at a singular point which is typically of the same multiplicity (cyclicity) or on a separatrix cycle which is also typically of the same multiplicity (cyclicity). This principle is a consequence of the principle of natural termination which was stated for higher-dimensional dynamical systems by A. Wintner who studied one-parameter families of periodic orbits of the restricted three-body problem and used Puiseux series to show that in the analytic case any one-parameter family of periodic orbits can be uniquely continued through any bifurcation except a period-doubling bifurcation. Such a bifurcation can happen, e.g., in a three-dimensional Lorenz system. But this cannot happen for two-dimensional systems. That is why the Wintner-Perko termination principle is applied for studying multiple limit cycle bifurcations of two-dimensional polynomial dynamical systems. If we do not know the cyclicity of the termination points, then, applying canonical systems with field rotation parameters, we use geometric properties of the spirals filling the interior and exterior domains of limit cycles. Using this approach, 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 Liénard polynomial system with an arbitrary number of singular points. By means of a similar approach, we study also three-dimensional polynomial dynamical systems and, in particular, complete the strange attractor bifurcation scenario for the classical Lorenz system connecting globally the homoclinic, period-doubling, Andronov-Shilnikov, and period-halving bifurcations of its limit cycles. All these systems are widely used in applications.
14. Detecting Dynamical States of Real World Time Series

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Nonlinear stellar pulsations has been an area where nonlinear time series analysis techniques have shown remarkable success. Variable stars are known to exhibit a variety of dynamical behaviors. These include limit cycle, intermittency, chaotic, quasiperiodic and strange nonchaotic behaviors. Inferring the underlying behavior from a light curve, that often contains missing data and is contaminated with noise, is a difficult task. In this work we show how to detect the underlying dynamical state when the datasets have missing data and noise. We deal with these issues by artificially simulating these effects, namely missing data and noise, in standard nonlinear systems. In the first part we will show how resilient the correlation dimension, $D_2$, is to gaps [1]. The use of $D_2$ as an indicator of chaos is evident form the wide use it has been put to. In the second part we look at how noise may cause a simple limit cycle that evolves with noise to be misinterpreted as being chaotic in origin, and a quasiperiodic attractor contaminated with colored noise may be misinterpreted as a strange nonchaotic attractor. We show that the bicoherence function can be used in these cases to successfully detect the actual dynamics [2].

In the context of missing data, interpolation can be dangerous as the features induced by the interpolation can lead to false positives [3]. We avoid interpolation and instead concatenate the data ignoring the gaps. We start from an evenly sampled time series of a Rössler system, remove data from the time series and merge the resulting time series together, ignoring gaps. The frequency of occurrence and size of the gaps are drawn from two Gaussian distributions. We observe the change in $D_2$ for the data with changing mean gap size and frequency. We then proceed to identify tolerable regions of gap size and frequency where the $D_2$ values do not vary much from the evenly sampled values.

We then identify variables stars that were previously suspected to be chaotic to act as test beds for our analysis. The light curves of these stars are taken from AAVSO, and are heavily unevenly sampled. We introduce a sampling time in these artificially by binning them. The bin size acts as an inherent sampling time, making the time series similar to the Rössler time series with missing data, considered earlier. The mean gap size and mean gap frequency are then calculated for these light curves. We show that for the cases where both fall into the tolerable region identified above, a saturated $D_2$ value can be obtained, and not so when they fall outside the considered region.

In the second part we show that Rössler limit cycles evolved with noise may be misinterpreted as being of chaotic in nature if one is to rely on standard quantifiers. However, using bicoherence, one can clearly distinguish between the two. Similarly, the attractor of a quasiperiodic doubly driven pendulum can be mistaken to be a strange nonchaotic attractor, if one is rely solely on techniques like spectral scaling of the strobed power spectrum to identify it. However, if we use a bicoherence filter to filter the peaks, before counting, the original scaling can be recovered, and the two states can be successfully distinguished.

These techniques are used then to analyze the light curves of variable stars from the Kepler space telescope. We analyze certain RRab Lyrae stars that are known to exhibit period doubling behavior [4]. The power spectra of these stars show peaks at frequencies other than the period doubled frequencies. We show through a bicoherence analysis that these peaks are of dynamic and not of stochastic origin. We also analyze the Kepler light curves of four RRc Lyrae stars suspected to be in a strange non chaotic state [5]. Applying the bicoherence filter we show that the scaling changes drastically for two of these stars and is retained for two of them, suggesting that the former are in a noisy quasiperiodic state while the latter are actually in a strange non chaotic state.
References


15. The Blinking Chimera in the Globally Coupled Kuramoto Model with Inertia

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Studying the globally coupled Kuramoto model with inertia, we demonstrate the blinking Chimera state. Simulating a system of $n = 7$ identical oscillators, we observe how a subset of oscillators forms a synchronized cluster, which stays intact for a very long transient time of the order of $10^6$, then breaks up, and finally reforms to give another long-lived cluster of the same size but with a different oscillator configuration. Using Lyapunov analysis, we characterize the conditions leading to the oscillator exchange. We study the transversal Lyapunov exponents and Lyapunov spectrum of the main cluster and the unsynchronized/partially synchronized cloud, and in particular show how the finite time exponents undergo a qualitative transformation from stable to unstable regime in the vicinity of the event.
16. The Easiest Way to Destabilize Mutualistic Networks

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Unravelling the interrelationship between structure and stability of ecological networks has been an important issue in theoretical biology. However, common approaches which consider ecological networks as high-dimensional dynamical systems have taken into account only linear stability analysis and are therefore restricted to a system’s sensitivity against small perturbations\cite{1}. We follow a new approach, assuming a plant-animal mutualistic system to be a multistable system in which one of the states represents the ‘desired’ dynamical regime enabling the largest number of coexisting species. In this case, the nonlinear stability of the desired state can be described by its ability to withstand non-small perturbations. As a measure for the nonlinear stability, we introduce the \textit{minimal destabilizing perturbation (MDP)} which is defined as the smallest perturbation being capable of inducing a regime shift to another undesired locally stable state (partial extinction). Determination of the \textit{MDP} is based on a Lagrange multiplier method which originates from the field of hydrodynamic stability theory \cite{2} and which is adapted to be applicable to dynamical networks. We then use the \textit{MDP} to locate weak points within bipartite mutualistic networks and derive topological features which adversely affect a state’s dynamic stability.

\textbf{References}

17. Voronoi Diagram from Charged Nanoparticles

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In this poster we show a simple concept to generate Voronoi diagrams using diffusion and aggregation process of like-charged nanoparticles by controlling interactions between nanoparticles in solid agarose gel.[1] Aggregation process of nanoparticles is triggered by electrostatic screening of negatively charged carboxyl protecting groups by sodium ions. Coupling diffusion of nanoparticles and sodium ions and precipitation of nanoparticles produces Voronoi diagrams. Voronoi cells consist of precipitated nanoparticles and their edges are aggregation-free and nanoparticles-free zones due to diffusion and fast aggregation process. Our work provides an idea how to control spatiotemporally the self-assembly of nanoscopic building blocks by a diffusion front.

References

18. Higher Order Return Maps for the Analysis of Period Doubling in the Model of Bray Liebhaفسky Oscillatory Reaction

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Bray Liebhaفسky (BL) reaction is the first discovered homogeneous oscillatory chemical reaction [1]. By numerically simulating the BL reaction in a continuously fed well stirred tank reactor (CSTR) with respect to flow rate as the control parameter, various dynamic regimes including regular oscillations, period doubling, quasiperiodicity and deterministic chaos have been explored [2]. More precisely, new structured types of chaos have been found between each two successive periodic states, and having forms resembling the neighboring periodic dynamics. Exploring period-doubling route to chaos, one was able to recognize and qualitatively and quantitatively distinguish the sequence of "period-doubling" chaos and chaos consisted of mixed-mode oscillations (the "mixed-mode structured" chaos), both appearing in regular order between succeeding periodic states. For this purpose, several methods were used for dynamical systems analysis, but return maps were found to be particularly useful [3]. In present paper, higher order return maps of the type \( X(n+2^m) = f(X(n)) \) were constructed using two techniques. First one was direct construction from the original Poincare section data, using the recorded order of section points. The other one was based on representing the first order map by the appropriate polynomial function \( P(X) \) and iterating \( P(P(X)), P(P(P(X))) \)... Second method was useful for prediction of periodic windows in period doubling sequences.

References

19. Statistical Features of Bacterial Turbulence

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Dense bacterial flows exhibit chaotic turbulence-like dynamics [1]. In contrast to hydrodynamic turbulence, this new class of turbulence shows a selection of length scales, characterized by the formation of stable vortices. Recently, a generalized Navier Stokes equation was proposed to model this turbulence-like phase in active matter [2, 3]. In this contribution, we report observations on Eulerian and Lagrangian statistical features of the bacterial turbulence system. We characterize the statistical quantities including the dispersion probability density function (PDF) as well as the Eulerian and Lagrangian velocity increment PDFs. We show that the small-scale statistics, both temporal and spatial, deviate from Gaussian when the system is sufficiently turbulent, with the deviations dependent on the energy injection. Our results provide insights into intermittency in this new class of turbulence.

References

20. Low-dimensional Chimera States: Regular, Chaotic and Heteroclinic

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We refer the appearance of weak chimera states in N=3 and N=4 Kuramoto model with inertia. Three different types of chimeras, characterized by the coexistence of frequency synchronized oscillators with at least one incoherent have been identified. We deal with regular (in-phase, anti-phase, etc.), chaotic (all oscillators behave chaotically) and heteroclinic chimera states. The latter develop in the form of heteroclinic cycling between the symmetric saddle chimeras, where the trajectory spends less (or more) time near at least one of the saddles, satisfying hereby the chimera criterion. This kind of the heteroclinic chimeras is found in narrow parameter regions for N=3, and for rather large parameter regions in the N=4 case.
21. Pattern Formation at the Border Between Marine and Terrestrial Ecosystems

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Spatial patterns are abundant in nature: ranging from abiotic systems like rocks and clouds to biotic systems like bacterial culture and animal skin. Theories involving Turing instabilities in reaction diffusion systems have been studied to understand the mathematical basis of such phenomena. While most of the literature involves systems with two or less components, pattern formation in ecological systems such as deserts and salt marshes is determined by three or even more interacting components.

In this work we study the formation of vegetation patterns in tidal areas at the transition zone between marine and terrestrial environments. We develop a model describing the growth of plants in the pioneer zone, which includes the interaction between biomass of seedlings and adult plants as well as the height of the sediment. The system is forced by the tides which, on the one hand, have a positive impact by bringing seeds into the system and, on the other hand, have a negative impact by removing seedlings and plants. We study under which conditions bare sediment, full vegetation cover or patterns of vegetation patches occur in the system and discuss the role of the different feedbacks involved.

References

22. Link Deletion in Directed Complex Networks

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With the growing importance of complex networks and their influence on our daily lives, it is imperative that we study and understand these networks so that we can learn from prior failures, design robust systems and utilize them better or simply just satisfy our curiosity about their function and behavior.

While a comprehensive study of networks would include many different aspects we are interested in studying their robustness to failures and attacks, either on the nodes or on the links. While considerable efforts have been made to understand the effects of node-deletion, the same cannot be said for link deletion [1, 2, 3]. Besides, the bulk of existing literature on link deletion is in the domain of undirected networks, while directed networks, despite their rich structural variety, have been either neglected or approximated to the undirected case. To make this study systematic and more general, we chose to work with a set of network models rather than actual real networks. In doing so, we also isolate the response of networks with specific properties to various kinds of link deletion mechanisms. To this end, we choose the following 4 directed network models: (a) Erdos Renyi (ER) network (b) a k-regular network (c) Watts-Strogatz (WS) network [4] and (d) a network that is scale-free in both the in and out degree distributions [5].

When it comes to designing and exploring an attack strategy, the 2 most important factors under consideration are the purpose of the attack and the amount of information needed to execute the strategy. In this work we investigate the effects of 3 attack strategies on the different networks mentioned earlier [2]. The first method is the random deletion of links. This strategy does not require any information about the network nor does it serve any specific purpose and therefore gives a reference behavior. The second strategy involves the removal of links based on their betweenness centralities. This strategy targets the flow in the network and requires global knowledge of the network to be executed. In the third strategy, the links are removed based on the product of the in-degree of the source node and the out-degree of the target node. This requires only local information about the nodes and is designed to affect the connectivity of the network.

All of the above-mentioned attacks result in changes in the network structure and the flow. We identify a set of metrics that capture these changes occurring in the network during the course of loss of edges [7]. To study the changes in global structure, we calculate the sizes of the Largest Strongly Connected Component (LSCC) and Weakly Connected Components (WCC). We calculate the Mean Clustering Coefficients (MCCs) to measure the structural changes occurring locally. To understand how flow in the network is affected, we measure the Average Inverse Path Length (A IPL) [6].

We look at the observations and results, based on the above metrics, and arrive at conclusions based on 2 directions of analysis. In the first approach, we compare the performance of the different networks under a given type of attack. This kind of analysis gain particular relevance when the intention is to prevent the given type of edge-loss or design systems that are resilient to the said type of edge-loss. In the second line of analysis, we compare the 3 attack strategies on a given network. This becomes important when the priority is to design an attack strategy to prevent or control a spreading process on the network.

References


23. New Results In Counting Process Theory

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The main goal of the presentation is to introduce new findings in the field of counting process theory. The motivation for dealing with this area is mainly driven by the vast possible applications of the obtained results. Particularly, counting processes are usually used to model systems of events consecutively coming in time or locations of some objects in one-dimensional space.

The presentation mainly focuses on the properties of so-called level counting process. This mathematical object is a specific kind of a counting process and it slightly generalizes the concept of a well-known renewal process. The generalization comes from the different choice of the origin of the process by which the respective underlying structure is significantly affected. To be more specific, the level counting process then exhibits linear and homogeneous behavior which allows one to derive respective moments in an elegant and applicable form. The presentation deals especially with the second central moment called rigidity. Actually, rigidity has been studied in many areas of applied probability and also theoretical physics as its dealt with for example in the publications [5] and [6]. Nevertheless, until this time, it has never been properly defined and as thoroughly studied as here.

Another major part of the presentation is devoted to the newly introduced quantity called corigidity. It is actually nothing more than the generalization of the rigidity concept in the form of the covariance function of a level counting process. As a matter of fact, the most essential results included in the presentation involve the asymptotic behavior of both rigidity and corigidity.

References

24. Data Analysis in Neuroscience: Using Spike Train Distances to Address Neuronal Population Coding

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During the last decade spike train distances [1-4] have become an essential means to characterize neural coding in a wide range of neurophysiological contexts. In a typical setup different stimuli are presented repeatedly and spike train distances are used to carry out a pairwise similarity analysis in order to evaluate whether responses to the same stimulus exhibit smaller distances than responses to different stimuli. With the increasing availability of multi-neuron recordings these kinds of analyses can now be performed not just for individual neurons but rather for simultaneously recorded neuronal populations.

Recently, the bivariate Victor-Purpura and the van Rossum distances [1, 2] have been extended to quantify dissimilarities between multi-unit responses. These new population measures [5, 6] have been designed such that they can estimate the discrimination performance of either the population as a whole ("summed population") or of individual neurons ("labelled line") or of interpolations between these two extremes. However, the question that these approaches fail to answer is the following: In cases the two extremes fail, which subpopulation within the larger population discriminates the presented stimuli best?

In this study we thus follow a complimentary approach and present an algorithm which addresses exactly this question. The brute-force approach of calculating the pairwise distance matrices and the stimulus discrimination performance for every possible neuronal subpopulation is not feasible even for moderate numbers of neurons. Instead, our algorithm relies on an iterative scheme which considerably restricts the number of subpopulations for which the pairwise distance matrices and the stimulus discrimination performance actually have to be calculated(Fig. 1).

Figure 1: Discrimination performance for different subpopulations of neurons. One subpopulation consisting of the first 47 neurons (marked in green) code for the different stimuli while the remaining neurons fire just randomly. The superimposed black line depicts the maximum discrimination performance for each row (i.e., the optimum obtained for a fixed size of the subpopulation). The maximum over all population sizes (green circle) is correctly obtained for the coding subpopulation.

The spike train distance that we use to evaluate whether the responses elicited by different stimuli can be distinguished is the SPIKE-distance [4]. Whereas distances like the Victor-Purpura or the van Rossum spike train distance rely on a time-scale parameter, the SPIKE-distance is parameter-free and time-scale independent. This allows for easy comparability of results obtained for vastly different firing rates (which
depend on the size of the pooled subpopulation). In contrast to the ISI-distance, the SPIKE-distance is sensitive to spike timing which is an important property in neuronal coding.

The three measures of spike train synchrony ISI-distance [3], SPIKE-distance [4] and SPIKE Synchronization [7] as well as the new directional measure SPIKE-Order [8] are implemented in the Matlab-based graphical user interface SPIKY [7], the Matlab command line library cSPIKE, and the Python library PySpike [9].

Acknowledgment

Research supported by the European Commission through the Marie Curie European Joint Doctorate ‘Complex oscillatory systems: Modeling and Analysis (COSMOS)’, project 642563 (TK and ER). T. Kreuz (email: thomas.kreuz@cnr.it), E. Satuvuori (email: eero.satuvuori@gmail.com), and M. Mulansky (email: mario.mulansky@gmx.net) are with the Institute for Complex Systems, CNR, Florence, Italy.

References

25. Chemical Oscillations with Sodium Perborate as Oxidant

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The peroxo compounds (H₂O₂ and K₂S₂O₈) represent one of the major constituents in many oscillatory systems. The known examples include the classical Bray (H₂O₂ – IO₃⁻ – MA – Mn(II)) reactions, some one-substrate pH-oscillators [H₂O₂ – S²⁻ – Cu(II); H₂O₂ – S₂O₄²⁻ – Fe(CN)₆⁴⁻], a few two-substrate pH-oscillators [H₂O₂ – SO₃²⁻ – Fe(CN)₆⁴⁻; H₂O₂ – SO₄²⁻ – S₂O₄²⁻ – Cu(II)] catalyzed H₂O₂ – SCN⁻ and S₂O₄²⁻ – S₂O₃²⁻ systems and the Ag(I)-catalyzed S₂O₈²⁻ – S²⁻ reaction. In this poster we demonstrate that sodium perborate (NaBO₃) which is a mild oxidant compared to the more effective H₂O₂ and S₂O₄²⁻ can act as an alternative oxidizing agent in oscillatory chemical reactions. So far the H₂O₂ has been successfully substituted by NaBO₃ in two oscillators: in the BO₃⁻ – S₂O₄²⁻ – Cu(II) flow system potential and pH-oscillations, in the strongly alkaline Cu(II)-catalyzed BO₃⁻ – SCN⁻ batch reaction potential oscillations were observed. In spite of the significant difference in the oxidizing nature of H₂O₂ and NaBO₃ we assume that the oscillatory cycle in the perborate substrate and the H₂O₂-substrate systems is similar, therefore the number of this new group can be considered to be borate mediated H₂O₂ oscillators. Mechanism is suggested and simulations are shown to explain the oscillatory behaviors observed in the two perborate based oscillators.
26. Network Inferring Using Rank Based Connectivity Measures

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The study of complex dynamical networks is an important tool to characterize real-world systems in natural and social science. The topology of the network is a key feature which determines the behavior of the system. Oftentimes, however, the connectivity structure of the system is not available. It is therefore important to infer the network topology by analyzing signals measured from the system. Here, we use a rank-based nonlinear interdependence measure developed for pairs of signals in [1]. However, pairwise approaches are prone to mistake spurious connections, mediated by a common driver or indirect connections, as direct connections. Therefore, we refine this approach to bridge the gap from pairs of signals to multivariate signals from networks. In particular, we introduce a correction term that conditions the pairwise results on the rest of the network. This refinement allows us to reconstruct networks more reliably than using solely the pairwise definition.

References

27. Pinning of 3D-chemical Waves to Highly Branched Heterogeneities

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Pinning of three dimensional excitation waves to inert obstacles in excitable media is of special interest due to its relevance to vortices in biological systems, especially in the context of human heart [1]. Scroll waves rotating around one-dimensional singularities, called filaments, can get pinned to unexcitable obstacles that results in an increase in their stability and lifetime [2]. Similar situations when arise in human heart have adverse effect on cardiac health. Vortices propagating in the myocardial tissue may anchor to anatomic obstacles like scars, fibrosis or coronary vessels thereby giving rise to stationary electrical signals that override the normal heart beat. Hence, the pinning of these vortices has attracted much attention in recent decades [3-4]. In this work, using the Belousov-Zhabotinsky reaction, we have experimentally studied the structure and dynamics of scroll waves in presence of a hexagonal mesh. It has been seen that filaments of different shapes and sizes can be made to pin to large ordered heterogeneities having multiple branching points. The final stable shape of the filament depends on its initial size, and its proximity to the nearest heterogeneity. The results have been verified with numerical simulations using the two-variable Barkley Model [5].

References

28. Criticality in Collective Mobility: Temporal Percolation and Spatial Variation

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Flexible, demand driven mobility systems have been shown [1, 3, 2] to be capable of performance similar to traditional taxi services at less cost to the environment and occupying less urban space. In order to deploy such a system in practice, one must understand how its quality of service (measured by, say, average waiting time) scales with the request rate. An especially interesting phenomenon is the critical load at which the system transitions from a well-performing state to a congested state.

We use a self-developed discrete-event based toolbox [4] to simulate such systems and quantify the benefits of flexible mobility systems over traditional taxis. Using tools from queuing theory we draw a parallel between such transitions and percolation. This "temporal percolation" framework allows us to derive values for critical loads at which suitably defined order parameters undergo a phase transition and compare the scaling exponents with numerically computed ones. We study how spatial parameters like the geographical density of the requests and the underlying network topology influence such transitions. Since spatial factors are by design absent in the queuing theory/temporal percolation paradigm, we investigate the spatial parameter regimes in which the queuing theory approach accurately predicts real-world behavior.

References

29. Generation of Soliton Bubbles in a Sine-Gordon System With Localised Inhomogeneities

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Nonlinear wave propagation plays a central role in the functioning of many physical and biophysical systems. Any disturbance in the propagation regime due to the presence of local external perturbations, such as localized defects or boundary interphase walls, may have important consequences in the behavior of the system. In the scattering of waves by such inhomogeneities, a crucial point to consider is that nonlinear waves exhibit a highly complex behavior. Apart from reflection, transmission, and annihilation, a local inhomogeneity can activate internal modes of solitons, producing many remarkable phenomena. In this poster, we give a short insight of our investigations on the complex phenomena that occur when two-dimensional sine-Gordon line solitons collide with localized inhomogeneities. On the basis of a one-dimensional theory, it is shown that the internal modes of sine-Gordon solitons can be activated, leading to the formation of bubble-like and drop-like structures. We also investigate their stability by the application of ring-like forces. An interpretation of the observed phenomena is given in the context of phase transitions theory. Implications in the problem of the stability, transport, and control of fluxons in disk-shaped Josephson junctions with current dipole devices are also discussed.

References


30. Transient Paths in a Hypernetwork of States Emerging in a Co-evolving Spiking Neuron Network

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We propose a paradigmatic model of how a network of spiking neurons can create complex responses at the higher level or representation in the corresponding hypernetwork [1]. First we consider a neuronal population as a network of interacting nodes-oscillators coupled by directed links which is the bottom level [2]. Depending on nodal dynamics the links become active or inactive thus forming different structural patterns in the network. Different input stimuli give rise to the activation of different distributed neuronal groups. We relate this distributed neuronal group specified by the common task to a corresponding hypersimplex. Hypersimplices are ordered, or structured, sets of nodes with an explicit relation; in other words, they exist at a higher level of representation than network’s nodes. In our model hypersimplices are specified by the coupling topology that leads to a certain cluster activity. In process of time the bottom-level network can exhibit different configurations corresponding to particular hypersimplices, i.e., at each moment only one hypersimplex can be found in the network. A structured set of hypercimplices determines a hypernetwork where the connections between hypercimplices describe their functional relations. In our model we assume that two hypercimplices are connected if the network can change its state from one hypersimplex to another due to the evolutionary rules governing its structure and dynamics. The co-evolution of structure and dynamics at the bottom-level network gives rise to a kind of traffic at the upper level in the hypernetwork. An actual path in the hypernetwork depends on the joint action of external inputs and the networks internal state. Each such path is a unique pattern of transient cluster activity for a given task performance and is robust in nonstationary environments [3].

Acknowledgment

This work was supported by the Russian Foundation for Basic Research (Project No. 15-02-04245).

References

31. pH Clock Reactions Inside Giant Lipid Vesicles

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Giant unilamellar vesicles (GUVs) are artificial chemical systems that can be employed as micro-sized compartments for chemical reactions [1]. Among the different methods available for the preparation of the GUVs, one of the easiest and with a high encapsulation yield is the so-called “droplet transfer”. This innovative technique first takes advantage of the facile compartmentalization of water-soluble solutes in w/o droplets, and then convert the solute-filled w/o droplets into GUVs [2]. We are currently exploiting this method to prepare giant vesicles encapsulating an enzymatic reaction: the conversion of urea in ammonia mediated by the urease. By taking advantage of the well-known bell-shaped reaction rate as a function of the pH, this reaction can show autocatalysis with a sharp increase in the pH. The induction period of the autocatalysis can be controlled to a large extent by varying the initial pH [3]. In order to follow the autocatalytic reaction in real-time, we devised an experimental system in which the enzyme is encapsulated together with a membraneimpermeable, pH-sensitive fluorophore. In this way, the reaction dynamics over time is monitored by an optical microscope equipped with a fluorescence module. Once prepared, the liposomes are dispersed in a solution containing the substrate (urea) and the inhibitor (e.g. acetic acid) that feed these micro-reactors. The permeability of the reactants, tuned by the lipid bilayer structure, affects the rate of reaction and the length of the induction period. Our results show that the lipid vesicles are permeable to the species involved in the enzymatic reaction: urea, acetic acid and ammonia (the product of the hydrolysis); moreover, we found several experimental conditions yielding the autocatalysis (clock reaction) [4]. Figure 1 is a representative example of a clock reaction inside vesicles with the corresponding plot Fluorescence intensity vs time. In this contribution, we will discuss how the permeabilities and the concentrations of the substrate and the inhibitor affect the dynamics of the reaction, investigating this aspect from both a theoretical and an experimental point of view. Indeed, the experimental results will be simulated with a kinetic scheme improved compared to our previous models [5,6].

![Figure 1](image_url)

Figure 1: Clock reaction inside giant vesicles. Experimental conditions: [urease]= 100 U/mL, [urea]= 0.01 M, [acetic acid]= $8 \times 10^{-6}$ M. The black dots of the plot are experimental data, the red line is a sigmoidal trendline.
References


32. Spatial Self-Organization in Inorganic Bromate Oscillators

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Pattern formation in chemical reaction-diffusion is the prototype of non-equilibrium self-organization. Although the detailed mechanisms of these systems are usually complex, relatively simple skeleton models can be used to reproduce the main dynamical properties. A popular method to study the formation of sustained reaction-diffusion patterns is based on the use of open one-side-fed reactors (OSFR). In an OSFR all space points are maintained at appropriate distance from thermodynamic equilibrium by the input of fresh chemical and withdrawal of end products, without introducing macroscopic fluid motions. Here, we present a numerical investigation of the dynamics of bromate oscillators, starting from the minimal version of them, in an OSFR. The aim of this work to find the appropriate conditions at which nontrivial sustained patterns can be observed experimentally in the type of bromate oscillators which shows oscillations only in open systems.
33. Freezing, Accelerating and Slowing Directed Currents in Real Time with Superimposed Driven Lattices

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A remarkable observation about time driven lattice setups, i.e. particles in a lattice which is shaken by external time-dependent forces of zero mean, is that they can show directed transport for an ensemble of particles, although there exists no net force. Such transport has been realized in a variety of setups leading to many intriguing effects and applications like on-site particle trapping, particle sorting and efficient velocity filters. Here we provide a generic scheme offering real time control of directed particle current using superimposed driven lattices. This scheme allows to accelerate, slow and freeze the ensemble transport on demand, by switching one of the lattices subsequently on and off. The underlying physical mechanism hinges on a systematic opening and closing of channels between transporting and non-transporting phase space structures upon switching, and exploits cantori structures which generate memory effects in the population of these structures. The scheme can be straightforwardly implemented in ac-driven optical lattices as well as using a superconducting quantum interference device (SQUID) setup with Josephson junctions operating in the underdamped classical regime of temperatures 1K. Our results should allow for real time control of cold thermal atomic ensembles in optical lattices, but might also be useful as a design principle for targeted delivery of molecules or colloids in optical devices.

References

34. From Weakly Chaotic Dynamics to Deterministic Subdiffusion Via Copula Modeling

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A basic principle in statistical physics is to connect dynamical aspects of a physical model to its statistical behavior. Such idea will be addressed here in the study of anomalous transport via copula modeling [1]. Considering Geisel-Thomae subdiffusive chain [2] as a weakly chaotic map [3], it is shown in the first place that the distribution of the sum of the displacements of jumps exclusively executed to either positive or negative direction obeys a Mittag-Leffler statistics. Inference tests are then performed to find which copula better coordinates the dependency across such random variables for the case $\alpha = 0.5$, showing thereby that Gumbel-Hougaard copula has the better agreement with the probability distribution function of the total displacement obtained from the numerical simulation. Moreover, there is a perfect match with the tails of such distribution, illustrating therefore the feature of such copula in describing extreme events [4]. In this way, the behavior of subdiffusion presented by such system is described by the ergodic properties of its weakly chaotic dynamics. A qualitative study for other $\alpha$ cases is presented in the end.

References

35. Anosov Diffeomorphism and Superdiffusion

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In our presentation, we propose a symplectic map derived from a Hamiltonian with periodic potential using the second order symplectic integrator. One obtains our map by revising a map in [1]. It is proven that the map is an Anosov diffeomorphism [2, 3, 4, 5] for certain parameter range. From the result in terms of the Anosov diffeomorphism, it holds that the Lebesgue measure is the SRB measure [6]. One obtains the Kolmogorv-Sinai (KS) entropy and Lyapunov exponent [7] and it is shown that the KS entropy is positive. By expanding the domain of the momentum, it is shown that the momentum obeys the Cauchy distribution [7, 8] and superdiffusion occurs for the parameter range. The mechanism of superdiffusion in our map is different from that in the standard map [9, 10].

References

36. Oscillatory Transformation in the Oxidation States of Cobalt Observed in the BrO$_3^-$ – SO$_3^{2-}$ – Co$^{2+}$ – Histidine CSTR System

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The coupling of pH-oscillator to pH-sensitive chemical equilibria offers a route to generate periodic changes in the concentration of the species that participate in the coupled equilibrium. This method was successfully applied to induce oscillations in the concentrations of many non-redox inorganic ions or to bring about periodic distribution of the species in stepwise complex formation reaction that takes place in a pH-oscillatory environment. In this poster we report a new version of the induced periodic phenomena. When a core oscillator is coupled to a chemical equilibrium where reaction can take place between the components of the subsystems, oscillations in the concentration or in the oxidation state of the participants may be observed. In the combined system which consists of the BrO$_3^-$ – SO$_3^{2-}$ pH oscillator and the Co$^{2+}$ – Histidine reaction the pH oscillates between 2.6 and 6.7, we expected to see periodical changes in the multiple absorption peaks in the spectra which stand for Co$^{2+}$, CoHis$^+$ and Co(His)$_2$, similarly to that obtained in our earlier study where the Ni$^{2+}$, NiHis$^+$ and Ni(His)$_2$ were convincingly identified in the BrO$_3^-$ – SO$_3^{2-}$ – Ni$^{2+}$ – Histidine system. In contrary to our expectation the spectra taken in the Co$^{2+}$-containing mixtures showed only one peak in the entire operational pH range, indicating the presence of one light absorbing species. According to literature examples the Co(II)-complexes easily undergo oxidation to Co(III)-complexes and this process is highly accelerated by SO$_3^{2-}$, the component of the core oscillator. During pH oscillatory cycle sulfite induced transformation between the two oxidation states in the BrO$_3^-$ – SO$_3^{2-}$ – CO$^{2+}$ – His coupled system. Qualitative description and some difficulties in the explanation of the induced oscillations will be briefly discussed in the poster.
37. An Unusual Behavior of the Sharp Ending Mode in the Briggs-Rauscher Oscillating Reaction

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The Briggs-Rauscher (BR) reaction is probably the most dramatic oscillating reaction, in which the oxidation of malonic acid (CH₂(COOH)₂) by a mixture of hydrogen peroxide (H₂O₂) and iodate (KIO₃) is catalysed by manganous ion (Mn²⁺) in acidic (H₂SO₄) aqueous solution [1-3].

It appears that oscillations are not the only interesting behaviour in the BR reaction [4, 5]. Depending on the initial concentrations, particularly on the ratio [CH₂(COOH)₂]/[IO₃⁻], the system may undergo a sudden transition from the steady state I (the state with low [I₂] and [I⁻]) to the steady state II (the state with high [I₂] and [I⁻]) [4]. Thus, the sharp ending mode represents the suddenly change in iodide concentration which occurs after a time delay, during which the system realized itself in the steady state I [5]. Although the ending mode in the BR reaction was in the focus of intensive experimental and theoretical investigations, the lack of evidence about reproducibility of the steady state I → II transition can be notices [4, 5].

In this study, random behavior of induction period for the steady state I → II transition was experimentally observed. It was found that the induction period strongly depends on external factors such as mixing rate, as well as shape and size of magnetic bar. On the other hand, it was found that the sharp ending mode in the BR reaction always occurs after well-defined and strongly reproducible oscillatory period. This rather unusual behavior of the sharp ending mode should be considered as a consequence of the local fluctuations (inhomogeneity), enlarged by nonlinearity at the later phase of the BR reaction.

References

38. The Effect of Temperature on Selectivity and the Dynamics of Product Formation During the Oscillatory Mode of the Phenylacetylene Oxidative Carbonylation Reaction

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The dynamics of reactant consumption and product formation in the oscillatory mode of the palladium-catalysed phenylacetylene oxidative carbonylation reaction over the temperature range of 0-40 °C were studied. Experiments were performed isothermally in a reaction calorimeter to correlate reactant consumption and product formation with the occurrence of oscillations and the heat released by the reaction. Reactant and products were quantified using GC-MS analysis. The dynamics of reactant and product formation throughout the course of the reaction (several days) were recorded. Oscillations in pH and accompanying pulses of heat were captured. The increase in period and amplitude of the pH oscillations that occurs as temperature decreases was found to continue at 0 °C.[1] The reaction heat was released in a pulsatile manner, resulting in a stepwise increase in the total energy released with the steps in energy being correlated with the pH oscillations. As the size of the pH oscillations increased, the amount of energy released during each step increased. It was also found that product selectivity changed with temperature: at 40 °C dimethyl (2Z)-2-phenyl-2-butenedioate was the major product whereas at 0 °C the major product was 5,5-dimethoxy-3-phenyl-2(5H)-furanone. The clear temperature dependence of the conversion rates as well as an increase in conversion as oscillations in pH developed were documented and an explanation for this behaviour is offered. In addition, a reaction pathway associated with selective formation of the observed products is proposed and aligned with the observed oscillatory phenomena.

References

39. Impact of Viscoelastic Coupling on the Synchronization of Self-Sustained Oscillators

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Synchronization properties of two viscoelastically coupled, modified Van der Pol oscillators are investigated. It is demonstrated that viscoelastic coupling leads to in-phase synchronization while elastic coupling favours anti-phase synchronization. To study the role of symmetry and nonlinearity, the restoring forces in the Van der Pol oscillators are extended to include nonlinear and asymmetric components. Above a certain threshold of asymmetry or nonlinearity of the restoring forces only in-phase synchronized oscillations are found to be stable. Chaotic solutions only appear if the restoring forces are asymmetric and the coupling incorporates viscosity.
40. Classical Subdiffusion and Quantum Localisation in Chaotic Hamiltonian System

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There is considerable interest in the transport properties of quantum systems whose classical counterpart displays chaos. One of the well-studied system in this respect is the delta-kicked rotor (DKR). Physically, DKR corresponds to a free particle which is periodically kicked by a sinusoidal potential. In the chaotic classical limit, DKR shows unbounded and diffusive energy growth while the corresponding quantised system shows absence of energy growth termed dynamical localisation (DL). DKR is a KAM system, i.e., it follows the Kolmogorov-Arnold-Moser (KAM) theorem. The main feature of KAM system is that with increase in the strength of perturbation the classical phase space structure like the invariant tori gradually break down leading to global chaos [1].

In contrast to such KAM systems, we study a non-KAM system as they are of great importance because of their application in tokamak fusion[2], plasma physics[3], and ion traps[4]. We consider a particle in a periodic potential well as a model of non-KAM system. The scaled Hamiltonian is

\[ H = \frac{p^2}{2} + V_{sq}(x) + k \cos(x) \sum_{n=-\infty}^{\infty} \delta(t-n). \]

In this, the first term is the kinetic energy of the particle, \( V_{sq} \) represents the periodic square well potential, \( k \) is the strength of a spatially periodic kicking potential applied at integer times. The potential \( V_{sq} \) has singularities at the position of potential barriers and this makes Eq. 1 a non-KAM system.

Classically, multiple sub-diffusive energy growth regimes with \( \langle E \rangle \propto t^{\mu} \) are observed. In contrast, in the quantum regime it shows DL, \( \langle E \rangle \) is a constant. These multiple sub-diffusive regimes can be attributed to the dynamics that proceeds through tori hops due to the presence of singular potential boundary. The log-log plot in Fig 1. illustrates two subdiffusive regimes in the classical system, denoted by black curve, characterized by exponents \( \mu_1 < 1 \) (green) and \( \mu_2 < 1 \) (red). The first regime characterized by the exponent \( \mu_1 \) arises due to the presence most of the particles inside the well region as seen in the inset A in Fig. 1. It is evident from the inset B in Fig. 1 that the second regime characterized by \( \mu_2 \) is due to particles populating the above-barrier region.

![Figure 1: Log-log plot of classical mean energy growth(\(\langle E\rangle\)) as a function of time(\(n\)).](image1.png)
We have studied how these classical non-KAM features affect the quantum dynamics of the system. The quantum system described by a Floquet operator whose spectra are of interest. The Floquet states, in the semiclassical limit, capture the dynamics of this non-KAM system. We have focused on the nature of decay of the Floquet states which determines the dynamics of the quantum system. Surprisingly, the structure of Floquet states can be divided into two parts, one part shows an extended structure while the other part decays as a power law.

In conclusion, we have studied a non-KAM system whose classical dynamics exhibits multiple subdiffusive regimes, a unique feature for Hamiltonian chaos. In quantum regime, this system shows dynamical localization and power-law decay of its Floquet states. In the semiclassical limit, quantum dynamics carries the imprint of non-KAM classical dynamics.

Acknowledgment


References

41. Global Phase Dynamics in the Finite Kuramoto Model

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Partial synchronization in the Finite-Size Kuramoto Model with distributed frequencies displays a much more complex dynamics than the solved case of the thermodynamic limit. Many questions, such as the time evolution of the mean value of the order parameter over time or the dependence on the sampling distribution remain unsolved. Due to the similarity to a thermodynamic phase transition, the scaling of fluctuations of the order parameter was quantified by [1, 2], [3, 4] and others. We now take a different perspective. Ensemble sizes are chosen rather small (∼ fifty) to observe considerable footprints of finiteness. The sample-to-sample variations of frequency distributions in natural populations imply differences in their collective behavior. In the finite all-to-all coupled Kuramoto model under consideration, the transition to a coupling domain with meaningful global phase definition depends on higher moments of the underlying natural frequency distribution - and so does the time evolution of this global phase. A semi-analytical analysis of the infinite model supports these observations.

References

42. Reservoir Computing with Complex Networks: Virtual and Real Networks

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Reservoir Computing is a machine-learning concept for data processing that utilizes the information spreading inside dynamical systems. It emerged from a machine-learning background as well as a biologically inspired model for the learning dynamics of the human brain. Reservoir computers have also been known as ‘Liquid State Machines’ and ‘Echo State Networks’.

The main components for Reservoir Computing are a dynamical system with a large phase space, called the ’reservoir’, a feed-in mechanism for the input data stream and a read-out layer with adjustable, i.e. trainable, strengths. With the right combination of these three components, the aim of this analog computer is to time-dependently extract information from the input data stream. Typical example tasks include the transformation of a timeseries, e.g. a nonlinear averaging or frequency-filtering, and also the prediction of future (unknown at the time of calculation) data points for chaotic timeseries.

In theory, the ’reservoir’ can be any dynamical system with a sufficiently large, but wellbehaved (e.g. not chaotic) phase space. The original concepts were devised for networks of maps or neural models, e.g. leaky-integrate-and-fire neurons. However, contemporary photonic experimental realizations of Reservoir Computing have mostly relied on a ‘delay-line’ approach, wherein a single node is used to create a virtual network via time-multiplexing.

In this poster we present a comparison of the delay-line approach of ’virtual networks’ with the original ’real network’ and intermediate schemes. We examine the cases of unidirectional and bidirectional rings of delay-coupled oscillators and compare their performance with virtual networks of the same overall size. We also investigate the connection between system dynamics, synchronization state and performance.

Figure 1: Synchronization state (left), dynamics (middle) and normalised root mean squared error for a nonlinear auto-regressive moving average task (right) of a pair of bidirectionally delay-coupled oscillators. Additionally, each oscillator is subject to a time-multiplexing by a factor of 200.
43. Effect of Human/Environment Interaction on the Nonlinear Dynamics of a Forest-Grassland Ecosystem: a Bifurcation Analysis

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Many ecosystems in nature are characterized by the coexistence of multiple stable states. In such systems sudden shift to one state to another may manifest as consequence of external disturbances. The most simple cases are bistable systems where two stable states coexist and depending on the initial conditions or on the external perturbations the system may approach to one of the two stable states. Frequently the external disturbances in ecosystems are caused by the human interactions and understanding the way disturbances influence the dynamics of ecosystems is very important to prevent and control ecological disasters which may manifest as a shift of the ecosystem to undesired stable states. Forest-grassland mosaic ecosystems are typical examples of ecosystems where two species (forest and grass) compete for the same food (soil, sunlight and space) [1-3].

Previous experimental observations as well as modeling research have shown that forest–grassland ecosystems behave like bistable systems where the bistability is mainly due to a feedback mechanism coming from the fire spreading [4-7]. In particular, it has been observed that if fire frequency is above a certain threshold, the ecosystem can be maintained in a grassland state, conversely if the frequency is low, forest state is stable. Thus, understanding how the stability of these two state is affected by external perturbations is of primary importance for the management and the control of the forests. Indeed a common way to manage forests in order to prevent fires is for example the deforestation [8-10] which is has been demonstrated to be able to maintain savanna in stable grassland state. Thus human actions have a direct consequence on the dynamics of forest-grassland ecosystems. From the other hand, the evolution of the ecosystem itself influences the human perception of the environment and thus it influences the human activities.

Because these feedback mechanisms, mathematical models has been developed which consider the human-environment systems as a whole dynamical system [11,12].

In this paper we perform the bifurcation analysis of the forest-grassland ecosystem model proposed by [12] which includes the human inference. The model couples a forest-grassland mosaic system to a dynamic model of rarity-driven perceptions of forest/grassland value. Once that the dynamics is studied, by varying different system parameter, we trace in a systematic way different bifurcation diagrams by means of a continuations technique. Moreover, we map in the parameter plane regions in which the system dynamics is qualitatively different by tracing the loci of the all bifurcations encountered in the parameter plane.

References

44. Turing Vegetation Patterns due to Interactions Between Water Availability and Auto-toxicity

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The development of a comprehensive theory of the formation of vegetation patterns is still in progress. Many experimental studies \([1, 2, 3]\), show the occurrence of different patterns, such as spots, labyrinths, gaps, and stripes, as well as plant rings and fungal fairy rings occur in a variety of natural environments \([4]\). It has been hypothesized that their development is affected by global phenomena like climate change \([7, 8]\). Such studies suggest that vegetation patterns in arid and semiarid environments might provide early warning signs of climate shifts and critical transitions \([5-8]\). The dishomogeneous distribution of water availability on the soil has been suggested as the main causal factor for the emergence of vegetation patterns. This hypothesis can be a good explanation of the occurrence of multiple vegetation patterns in arid and semi-arid regions, but it does not justify the presence of vegetation patterns in humid environments. Marasco et al. 2014 proposed the plantsoil negative feedback (NF) has an alternative mechanism of the emergence of vegetation patterns. Mechanisms involved in the NF include the presence of soil borne pathogens, the changing composition of soil microbial communities (Kulmatisky et al. 2008), and the accumulation of auto-toxic compounds from decomposing plant litter \([9, 10]\). We analysis a the nonlinear dynamics and the emergence of the vegetation pattern formation modeled by a toxicity-mediated system. This model consists of three PDEs accounting for a dynamic balance between biomass, water, and toxic compounds. Different (ecologically feasible) regions of the models parameter space give rise to stable spatial vegetation patterns in Turing and non-Turing regimes. Strong negative feedback gives rise to dynamic spatial patterns that continuously move in space while retaining their stable topology.

References

45. Dynamics of Four Almost Identical Oscillators Coupled Via Excitatory Pulse Coupling With Time Delay

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We investigate theoretically a network of four chemical oscillators with slightly different frequencies. Oscillators are connected via excitatory pulses, which can be characterized by two parameters: $C_{ex}$, the coupling strength, and $\tau$, the time delay. We consider two topologies of the network connection: unidirectional coupling on the ring and "all-to-all" coupling. Two models of chemical oscillators have been considered: the kinetic model of the Belousov-Zhabotinsky (BZ) reaction and the model of phase oscillators.

In the case of unidirectional coupling on the ring, numerical modelling reveals 8 regular dynamical modes. They can be divided into two groups: symmetrical oscillations (Walk, Antiphase, Walk Reverse, and In-Phase) and asymmetrical (Pack Walk, Pack Walk Reverse, Asymmetrical type 1, and Asymmetrical type 2). Period $T$ of the oscillations for the first group of modes depends on the time delay $\tau$, while period $T$ is independent of $\tau$ for the second group. Formulas which precisely describe boundaries of the stability regions of the listed modes in the $C_{ex}$-$\tau$ plot have been derived.

For the network with "all-to-all" coupling, 13 regular modes can be specified, which can also be classified as follows: $\tau$-dependent (two types of Splay mode, the 3-Cluster modes, the 2-Cluster mode, Antiphase, and In-Phase) and $\tau$-independent (two types of Almost In-Phase mode, the Almost 3-Cluster modes, the Almost Antiphase, and the Pack Splay mode).

Note that two additional groups of modes exist for the both connectivities when the kinetic model is used: (a) the Complex modes and (b) the OS (Oscillation-Suppression) modes.

The system demonstrates multistability at large enough values of the coupling strength $C_{ex}$. Detuning (=slight difference in native frequencies of oscillators) have a considerable influence on the stability regions of the modes. In particular, a small detuning (2-5%) makes the In-Phase mode unstable in a very large area of the $C_{ex}$-$\tau$ plane. Detuning is responsible for the narrow metastable zones between the stability regions of the regular modes. We hypothesize that the increase in the detuning broadens this zones.
46. Tracing Peptidization in the Equichiral and Inequichiral α-amino Acid Solutions with Aid of Turbidimetry and the Circular Dichroism (CD)

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In this study, a comparison is made between the dynamics of the spontaneous oscillatory peptidization of the selected α-amino acids in the monocomponent and the binary equichiral mixtures (L, D, L-L, or D-D) on the one hand, and in the respective binary inequichiral mixtures (DL, L-D, or D-L) on the other. As the dynamics of peptidization results in the formation of insoluble peptide particles, it is traced with aid of turbidimetry in the continuous registration mode (for 14 days at 25°C). From the obtained plots of the turbidity changes, a conclusion can be drawn about the similarity of patterns of the turbidity changes valid for the monocomponent and the binary equichiral samples on the one hand, and the dissimilarity of the turbidity patterns valid for the binary inequichiral samples on the other. This observation suggests that spontaneous peptidization running in the solutions of the equichiral amino α-acids can probably result in the formation of the left- or right-handed α-helical peptide structures (and possibly of the other α-helix-based secondary peptide structures like, e.g., peptide bundles or coils). In the inequichiral binary α-amino acid mixtures, peptidization engages the L and D α-amino acid molecules randomly (as confirmed by means of mass spectrometry, ESI-MS) and hence, it can be speculated that the formation of the equichiral heptades (or the entire α-helices) in these peptide structures is rather impossible. In order to verify our hypothesis as to the formation of the α-helical structures in the solutions containing equichiral α-amino acid molecules and as to the lack of similar structures in the solutions containing inequichiral α-amino acid molecules, the measurements with aid of the spectroscopy of circular dichroism (CD) in the far UV range were performed, which confirmed our speculations initially based on the turbidimetric results.
47. The pH Oscillatory Behavior in Glucose Oxidase-Ferricyanide System

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Our experimental work is focused on observation of dynamic regimes in the glucose oxidase-glucose-ferricyanide-NaOH system in continuous stirred tank reactor. We measured pH and found hysteresis when varying the flow rate as known from earlier work. In addition, the region of hysteresis is accompanied by small regions of various types of pH oscillations. The pH and the temperature of the system is continuously monitored, while the variable parameter, flow rate, is changed stepwise enabling to observe hysteresis loops and bistability of pH for a set of inlet concentrations of D-glucose and NaOH. The neighborhood of the upper and lower boundary of the bistable region is closely inspected by performing long run experiments for suspected occurrence of pH-oscillatory behavior. We report occurrence of small amplitude pH-oscillations with peaks averaging at ~0.1 pH units, medium pH oscillations with the amplitude ~0.5 pH and large oscillations with the amplitude ~2 pH.
48. Multiday Oscillatory Dynamics of Aqueous Systems

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Aqueous systems are indispensable constituents of the most electrochemical experiments [1]. However, to our knowledge there have been no multiday lasting electrochemical studies in open circuit dealing with system response when only deionized water is used. In this study, we used Pt-wire electrode (Metrohm) and Ag/AgCl (Metrohm) double junction reference electrode to investigate their electromotive force (EMF) changes in 100 ml deionized water (R=18.2 MΩ) at T=30°C and at ambient temperature, where T≠const. in closed well-stirred tank reactor. The electrochemical cell was in some experiments covered with Al foil from the outside to protect it from the light and to serve as Faraday shield. Control tests were also performed with 100 ml sulfuric acid solution (pH=3) and 0.15 M KCl solution at T=30°C, but without the use of Al foil. Each our experiment lasted for 7 days. The results have shown diurnal oscillations in EMF between electrode couple in deionized water, with 15-30 mV amplitudes, regardless of whether the temperature is constant or not, and EMF oscillations absence when Al foil was applied. It was also shown that periodic EMF oscillations between electrode couple in sulfuric acid did not appear until the 4th day of investigation and had amplitude of only ≈2 mV. On the other hand, diurnal oscillations in EMF between electrode couple in 0.15 M KCl solution were present during the entire experiments, with the amplitude ≤5 mV. The preliminary results raise the question of the origin of EMF oscillations between Pt and Ag/AgCl electrode in our experiments. The answer to that question would provide new insights into the challenges of the multiday potentiometric examinations of aqueous systems or possibly any electrochemical experiment in it.

References

49. Dynamics of pH Oscillators in a Two Side Fed Reactor

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Pattern formation in chemical reaction-diffusion systems with positive and negative feedback serve as a prototype of non-equilibrium self-organization. Hydrogen ion autoactivated systems with appropriate negative feedback, pH oscillators, are preferably used to study reaction-diffusion phenomena [1]. These systems are capable to show a wide range of spatiotemporal phenomena from spatial bistability and oscillations to the formation of stationary patterns. The experiments are typically performed in open spatial reactors, which allow to feed all space points of a porous material (e.g., a hydrogel) in order to maintain the system far from equilibrium, without introducing macroscopic fluid motion. The feed can only be made by diffusive exchanges of matter with the environment at the boundaries of the system. The spatiotemporal dynamics of pH oscillators have been mostly explored in one-side-fed-reactors, where all reagents are fed through a unique continuous-flow stirred tank reactor (CSTR) and the feed composition at the CSTR/gel boundary relies on the chemical state of the CSTR. Here, apply a two side fed reactor (TSFR) geometry, where complementary sets of chemicals are provided at opposite faces of the gel. This configuration induces cross composition ramps of the chemicals between the feed boundaries. This asymmetric feeding mode avoids the development of the temporal instabilities in the feed tanks and allows us to study pattern formation in presence of cross gradients. It is widely accepted, that the graded distributions of morphogens play important roles in biological pattern generation [2]. By using numerical simulations with a general model of the pH oscillators we observed spatial bistability and oscillations in a presence of counter gradients of the chemicals. The nonequilibrium phase diagram of the system shows a typical cross shaped topology. Two types of spatiotemporal oscillations have been found, one with large and the other with small amplitude. The interaction of them leads to the formation of mixed mode oscillations. We discuss the role of gradients of the chemicals in the development of the observed phenomena.
50. Spacing Distribution of Localized States and Their Nearest Neighbours in Quantum Chaos

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The study of level spacing distributions in quantum chaos has been inextricably linked with results from Random Matrix Theory (RMT). The Bohigas-Giannoni-Schmit Conjecture states that the spectra of quantum systems, whose classical versions exhibit chaos, have a spacing distribution which matches that of the Gaussian Orthogonal Ensemble (GOE), well-studied in RMT [1]. Deviations from these results can be attributed to quantum phenomena like localization and dynamical tunneling [2]-[5].

Some quantum chaotic systems contain a class of localized states, called ‘scarred’ states, which are quantum manifestations of unstable periodic orbits in the classical counterparts of these systems. The wave functions are localized in the vicinity of these periodic orbits, leading to the so-called scars. This phenomenon has been well studied in various systems [6][7].

However, the spacing distribution between energy levels corresponding to scarred states and their nearest neighbors that (usually) correspond to chaotic or ‘random’ neighbors has not been studied so far. We propose a one-parameter RMT model with the parameter $\mu$ representative of the coupling between localized states and their nearest neighbors. This model is applicable for systems that follow either Gaussian Orthogonal Ensemble (GOE) or Gaussian Unitary Ensemble (GUE) statistics.

This 3x3 model can reproduce the distribution of the ratio of level spacings between a localized state and its chaotic or ‘random’ neighbors. This ratio is defined as follows: If $E_n$ is the $n$-th eigenvalue of the system, then the spacing between nearest neighbors is defined as $s_n = E_{n+1} - E_n$. From this, the ratio of spacings, $r_n = s_{n+1}/s_n$ is calculated and its distribution $P(r)$ is obtained. From this, the Wigner surmise can be derived [8], and it takes the form:

$$P_W(r) = \frac{8}{27} \frac{(r + r^2)}{(1 + r + r^2)^{5/2}}$$

This quantity (the distribution of ratios) is used as it does not require unfolding of the spectrum.

![Figure 1: The blue curve denotes the formula for distribution of the ratio of consecutive level spacings $P(r)$ for GOE. The broken line is the histogram obtained by numerical fitting for GOE from the 3x3 model, with the value of the parameter $\mu = 1$. The value $\mu = 0.7$ obtained from the model corresponds to the distribution of the ratio of spacings between a localized state and its nearest neighbors for the quartic oscillator.](image)

The applicability of this model has been demonstrated for quantum chaotic systems like coupled quartic oscillators and quantum billiards. In these models, the localized states are identified using information entropy. From this, the spacing between energy levels corresponding to a localized state and its nearest
neighbor is calculated and the distribution of the ratio of the spacings is determined. The value of the model parameter $\mu$ corresponding to this distribution is then found.

References

51. Flow-driven Morphology Control in Transition Metal-oxalate Systems

Eszter Tóth-Szeles\textsuperscript{1}, Brigitta Müller\textsuperscript{1}, Dezső Horváth\textsuperscript{2}, and Ágota Tóth\textsuperscript{1}

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Transition metal oxalates are widely used precursors of metal oxide or metal catalysts. We experimentally investigate the spatiotemporal precipitate formation in the chemical reaction of sodium oxalate and various transition metal salts in a flow-driven system. With the new flow-injection technique, the chemical composition and the morphology of the precipitate can be conveniently controlled. When the more dense aqueous solution of metal ions is pumped into the less dense thin layer of oxalate solution, a gravity current forms which influences the sedimentation of the solid particles by creating filamental structure at the bottom of the reaction vessel if the nucleation is sufficiently slow \cite{1}. The emergence of the radial macroscopic filaments depends on the flow rate and the density difference between the solutions \cite{2}. As control experiments, we have also investigated the precipitation process in a well-stirred batch system. Besides the characterization of the spatiotemporal dynamics, the microstructure of the solid materials is also analyzed by various analytical techniques like scanning electron microscopy, X-ray powder diffractometry and X-ray fluorescence analysis. Numerical calculations are also carried out using the Navier-Stokes equation for an incompressible fluid. The model is based on the spreading of a dense liquid from an inlet to mimic the experimental setup. The formation of the gravity current is described quantitatively, a scaling law related to the flow pattern is determined, and the results corroborate the experimental findings.

References

52. Scattering of Bulk Strain Solitons in Layered Structures

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In this poster we will consider the modeling of long longitudinal bulk strain solitary waves in delaminated elastic bars. We describe the dynamics of a symmetric perfectly bonded layered bar with delamination and present numerical results for the full scattering problem as well as for a semi-analytical technique. The results are shown to be in good agreement with each other and the theoretical predictions, and fission occurs in the delaminated section - a clear sign of the presence of delamination [1, 2].

Extending our studies to a layered bar with a soft bonding layer, modeled by a system of coupled Boussinesq equations [3], we again consider the behavior of the waves in a delaminated region of the waveguide [4]. Numerical results are compared for the full scattering problem and the semi-analytical approach, as well as considering the case where we have a delamination of finite length. The behavior of the wave in this second bonded region varies dependent upon the length of delamination, and has the potential to help control the integrity of layered structures.

References

53. Stochastic Kinetics or Imperfect Mixing Driven Irreproducibility?

László Valkai

University of Pécs

Stochastic kinetics has a very extent mathematical description with various potential applications. In case of nonlinear redox reactions three systems were proven to exhibit irreproducible individual kinetic curves, though a statistically meaningful number of samples leads to the same cumulative probability distributions. We shall demonstrate unambiguously that the fate of periodate-arsenous acid reaction in case of individual runs is determined at the first couple of seconds when the system is per se inhomogeneous and as expected the stochastic behavior can be eliminated by enhancing the mixing procedure.
54. Binary Test for Partially Predictable Chaos

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The initial exponential divergence of close-by trajectories is one of the tell-tale signs for deterministic chaos [1] in dissipative dynamical systems. This initial process of decorrelation is characterized by a positive maximal Lyapunov exponent and the corresponding time scale, the Lyapunov prediction time, up-to which there is still a certain amount of information about the initial configuration. The initial decorrelation is followed by a final loss of correlation due to diffusion on the chaotic attractor. For strong chaos both exponential and diffusive decorrelation happen on the same time scale, thus all predictability is lost within the order of the Lyapunov prediction time. However, for partially predictable chaos (PPC), for which the diffusion happens on a significantly longer time scale, predictability stays finite for exceedingly long times. This happens, e. g., when the topology of the attractor is equivalent to closed chaotic braids. Then the initial loss of correlation is caused by a divergence perpendicular to the braid, while the diffusion along the attractor is much slower.

As many of the standard tests for chaos rely on correlation measures their classification of PPC is mostly ambiguous. In addition we find that for PPC the maximal Lyapunov exponent can become arbitrary small. Therefore we introduce a novel test for chaos based on the cross-distance scaling of initially close-by trajectories [2]. Our test is capable of robustly distinguishing chaos, including PPC, from regular flow in a 0-1 fashion. Besides an analytic motivation for the distance scaling, we present the results of our test for the Lorenz system [3], for which we find all three dynamical regimes strong chaos, PPC, and regular flow.

Using the finite-time cross-correlation of initially close-by trajectories, another effectively binary test, we are also able to distinguish strong chaos and PPC due to the different time scales in the decorrelation process. The combination of both tests is capable of discriminating all three dynamical regimes robustly and in an unambiguous 0-1 fashion.

References

55. Target Points in Neural Dynamics

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In neural networks differences in time scales, spanning the range from milliseconds (membrane potential) to hours (plasticity), play an important role in cognitive processing tasks. Modeling such networks by dynamical systems with distinct time scales one finds that the fixpoints of the fast subsystem are destroyed by the additional time evolution of the slow subsystem. The remnants of the destroyed fix points are present in the full system as transiently *attracting states* [1] forming the slow manifold. These relics can guide the flow across the manifold and thus strongly influence the behavior of the overall system. Especially in high dimensional systems it is not trivial to compute the entire slow manifold, neither to determine its effect on the overall dynamics.

As a resolution, in this contribution we elaborate the concept of stable/unstable *adiabatic fixpoints* (AFP), which are the stable/unstable fixpoints of the fast subsystem in the adiabatic limit, i.e. when the slow subsystem is infinitely slow, only acting as parametric variable [2]. We then can map each state of the overall dynamics onto exactly one *target point*, i.e. the stable AFP that the system would converge to in the adiabatic limit. Even in a high dimensional system we thus find for any given trajectory a lower dimensional manifold of effective transiently attracting states. Further, we investigate the average distance between a trajectory and its target manifold and the distribution of distances. Thereby we are able to quantify the effect of the transiently attracting states on the overall dynamics.

We present and illustrate our results for an autonomous three-neuron system that consists of continuous-time point neurons [3] with an intrinsic adaption being substantially slower than the primary neural activity. Depending on the symmetry of the system we find attractors that are dominated by the target points and symmetry protected cases that do not settle close to any transiently attracting state. We show how these states can be classified using the respective target points. For completeness we also present a chaotic attractor of the same system and its transiently attracting states, gaining further insight on the origin of chaos.

**References**

56. Quantum Signatures of Synchronization

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Understanding collective dynamical phenomena constitutes a topical challenge across physics and beyond, with distinct implications for the classical and quantum realms. How collective phenomena in classical and quantum worlds are linked is largely unknown. Synchronization constitutes one of the most basic cooperative dynamics in classical systems. It indicates the locking of states of coupled classical units and governs the dynamics of physical, chemical, and biological systems. Entanglement constitutes the most fundamental phenomenon in many-body quantum systems and indicates correlations that are genuinely quantum mechanical.

In this talk I will present a direct link between classical synchronization and quantum entanglement for a system of nonlinearly coupled oscillators. In the mean-field limit this system bears the celebrated Kuramoto model. Intriguingly, transient squeezing and persistent number entanglement emerge through and exactly at the transition to classical synchronization. Moreover, the growth rate of number fluctuations is directly given by the classical phase order parameter. I discuss how this quantum-classical link may be experimentally verified in ongoing experiments with ultracold atoms in optical lattices.

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