Physics of Socio-economic Systems Division
Fachverband Physik sozio-ökonomischer Systeme (SOE)

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Overview of Invited Talks and Sessions

(Lecture hall GÖR/0226; Poster P4)

Invited Talks

SOE 2.1	Mon	9:30–10:00	GÖR/0226	**Memory and equilibrium in collective animal behaviour** — •Thierry Mora
SOE 5.1	Tue	9:30–10:00	GÖR/0226	**Network Science in Criminology: Insights from Empirical Case Studies** — •Masarah Paquet-Clouston
SOE 8.1	Wed	9:30–10:00	GÖR/0226	**Dynamics and Structure in Temporal Networks** — •Natasa Djurdjevac Conrad
SOE 14.1	Thu	9:30–10:00	GÖR/0226	**Generative AI and diffusion models: a statistical physics approach** — •Giulio Biroli
SOE 16.1	Thu	11:30–12:00	GÖR/0226	**Tipping in Strongly Perturbed Open Networks** — •Marc Timme, Georg Börner, Marisa Fischer, Julian Fleck, Seungjae Lee, Philip Marszal, Gwendolyn Quasebarth, Malte Schröder, Moritz Thümler
SOE 17.1	Fri	9:30–10:00	GÖR/0226	**What can we learn from neural quantum states?** — Brandon Barton, Juan Carrasquilla, Anna Dawid, Antoine Georges, Megan Schuyler Moss, Alev Orfi, Christopher Roth, Dries Sels, Anirvan Sengupta, •Agnes Valenti
SOE 17.6	Fri	11:15–11:45	GÖR/0226	**Creativity in generative AI** — •matthieu wyart

Young Scientist Award Session

SOE 7.1	Tue	14:00–14:30	GÖR/0226	**What's that noise? Why does it make a difference? And why am I thinking about it all the time?** — •Dirk Brockmann
SOE 7.2	Tue	14:45–15:30	GÖR/0226	**How things spread: Complexity and criticality of inhomogeneous spreading models** — •Laurent Hébert-Dufresne

Invited Talks of the joint SKM Dissertationspreis 2025 Symposium (SYSD)

See SYSD for the full program of the symposium.

SYSD 1.1	Mon	9:30–10:00	HSZ/0002	**Stochastic-Calculus Approach to Non-equilibrium Statistical Physics** — •Cai Dieball
SYSD 1.2	Mon	10:00–10:30	HSZ/0002	**Nonuniform magnetic spin textures for sensing, storage and computing applications** — •Sabri Koraltan
SYSD 1.3	Mon	10:30–11:00	HSZ/0002	**Anomalous Quantum Oscillations beyond Onsager's Fermi Surface Paradigm** — •Valentin Leeb
SYSD 1.4	Mon	11:00–11:30	HSZ/0002	**Coherent Control Schemes for Semiconductor Quantum Systems** — •Eva Schöll
SYSD 1.5	Mon	11:30–12:00	HSZ/0002	**On stochastic thermodynamics under incomplete information: Thermodynamic inference from Markovian events** — •Jann van der Meer

Invited Talks of the joint Symposium "The Sustainability Challenge: A Decade of Transformation" (SYSC)

See SYSC for the full program of the symposium.

SYSC 1.1	Mon	15:00–15:30	HSZ/AUDI	**Open-Endedness and Community-Based Approaches to Sustainability Challenges** — •Hiroki Sayama
SYSC 1.2	Mon	15:30–16:00	HSZ/AUDI	**Education as a Social Tipping Element: Evidence from Climate and Physics Education Research** — •Thomas Schubatzky
SYSC 1.3	Mon	16:00–16:30	HSZ/AUDI	**Mechanistic and Material Perspectives on Enzymatic Hydrolysis of Semicrystalline Polyesters** — •Birte Höcker
SYSC 1.4	Mon	16:45–17:15	HSZ/AUDI	**Decarbonization Options for Industry** — •Uwe Riedel
SYSC 1.5	Mon	17:15–17:45	HSZ/AUDI	**Impacts of Cosmic Dust and Space Debris in the Terrestrial Atmosphere** — •John Plane

Invited Talks of the Symposium "Tipping Points in Social and Climate Systems" (SYTP)

See SYTP for the full program of the symposium.

SYTP 1.1	Thu	15:00–15:30	HSZ/AUDI	**Social Tipping in Heterogeneous and Polarized Populations** — •Sara Constantino, Sonke Ehret, Elke Weber, Sonja Vogt, Charles Efferson
SYTP 1.2	Thu	15:30–16:00	HSZ/AUDI	**Tipping points and regime shifts in coupled social-climate systems** — •Chris Bauch
SYTP 1.3	Thu	16:00–16:30	HSZ/AUDI	**How to tune Earth system models toward tipping?** — •Sebastian Bathiany, Niklas Boers
SYTP 1.4	Thu	16:45–17:15	HSZ/AUDI	**Algorithmic amplification and contextual sensitivity in political information exposure** — Iris Damião, Ana Vranic, Paulo Almeida, Lília Perfeito, •Joana Gonçalves de Sá
SYTP 1.5	Thu	17:15–17:45	HSZ/AUDI	**The complex interplay between democracy and platform power** — •Philipp Lorenz-Spreen

Sessions

SOE 1.1–1.2	Sun	16:00–18:15	HSZ/0004	**Tutorium: Physics of Behavior (joint session SOE/TUT/DY)**
SOE 2.1–2.10	Mon	9:30–12:45	GÖR/0226	**Focus Session: Physics of Behavior (joint session SOE/DY)**
SOE 3.1–3.4	Mon	9:30–10:30	MER/0002	**Sustainability: Challenges and Solutions (joint session UP/CPP/SOE)**
SOE 4.1–4.9	Mon	18:00–21:00	P4	**Poster Session**
SOE 5.1–5.3	Tue	9:30–10:30	GÖR/0226	**Network Science**
SOE 6.1–6.7	Tue	10:45–12:45	GÖR/0226	**Mobility, Traffic Dynamics, Urban and Regional Systems**
SOE 7.1–7.2	Tue	14:00–15:30	GÖR/0226	**Award Session: Young Scientist Award for Socio- and Econophysics (YSA)**
SOE 8.1–8.4	Wed	9:30–11:00	GÖR/0226	**Networks, From Topology to Dynamics I (joint session SOE/DY)**
SOE 9.1–9.5	Wed	11:30–12:45	GÖR/0226	**Economic Models**
SOE 10.1–10.3	Wed	15:00–15:45	GÖR/0226	**Networks, From Topology to Dynamics II (joint session SOE/DY)**
SOE 11.1–11.5	Wed	15:45–17:15	GÖR/0226	**Polarization**
SOE 12.1–12.3	Wed	17:15–18:00	GÖR/0226	**Statistical Physics of Politics**
SOE 13	Wed	18:00–19:30	GÖR/0226	**Members' Assembly**
SOE 14.1–14.6	Thu	9:30–11:15	GÖR/0226	**Focus Session: Physics of AI I (joint session SOE/DY)**
SOE 15.1–15.6	Thu	11:15–12:45	ZEU/0118	**Networks: From Topology to Dynamics III (joint session DY/SOE)**
SOE 16.1–16.4	Thu	11:30–12:45	GÖR/0226	**Tipping Points in Social and Climate Systems (accompanying session for SYTP)**
SOE 17.1–17.10	Fri	9:30–12:45	GÖR/0226	**Focus Session: Physics of AI II (joint session SOE/DY)**

Members' Assembly of the Physics of Socio-economic Systems Division

Wednesday 18:00–19:30 GÖR/0226

- SOE poster award
- Report
- Election
- All other business

SOE 1: Tutorium: Physics of Behavior (joint session SOE/TUT/DY)

The emerging field of the physics of behavior seeks to quantitatively characterize complex behavior in biological agents under naturalistic conditions, using tools from dynamical systems theory and statistical physics. Even in simple organisms, behavioral richness demands new methods of measurement and analysis, as well as new theoretical frameworks. In the absence of a first-principles theory, data-driven approaches are essential, and the many interacting degrees of freedom call for descriptions capable of handling high-dimensional systems.

This tutorial introduces how concepts from dynamical systems theory and statistical physics can be applied to quantify behavior across biological scales and to develop simple yet predictive models. It is intended for physicists at all levels, beginning with graduate students, who are interested in computational approaches to modeling animal behavior. The tutorial is accompanied by an openly accessible code repository to support hands-on exploration of selected topics.

Time: Sunday 16:00–18:15 Location: HSZ/0004

Tutorial SOE 1.1 Sun 16:00 HSZ/0004
Physics of Behavior — •Greg Stephens — Vrije Universiteit Amsterdam, Amsterdam NL — OIST Graduate University, Tancha, JP

In these tutorials we view behavior as a complex dynamical system and we incorporate insights from dynamical systems theory and statistical physics to quantitatively capture what animals do. Of course, such theory was not historically developed to understand animal behavior, and there are particular challenges associated with the modeling of living systems. Of these, the most important is a lack of first-principles theory necessitating a data-driven approach.

In the first half of our session we will introduce two primary concepts. (1) Posture Space Analysis via Dimensionality Reduction. We explore posture space analysis by demonstrating how to decompose high-dimensional postural data into a few meaningful eigenpostures using Principal Component Analysis (PCA). The dataset used comes from C. elegans posture tracking. (2) Posture Space Dynamics via State Space Reconstruction. We review the concepts of state space and chaotic systems through a toy model. We then introduce a modern data-driven technique for state space reconstruction.

15 min. break

Tutorial SOE 1.2 Sun 17:15 HSZ/0004
Physics of Behavior — •Antonio Carlos Costa — Paris Brain Institute, Paris, France

Animal behavior is inherently nonlinear and multiscale, spanning millisecond movements to hour-long strategies. In the second half of our session, we will complement first-principles approaches with data-driven methods to identify multiscale dynamics in behavioral data.

We will present three key techniques: (1) state space reconstruction combined with transfer operators to extract long-timescale modes from partial observations, (2) coarse-grained modeling to infer slowly-varying behavioral dynamics and explain heavy-tailed statistics, and (3) a multiscale distance metric for reconstructing behavioral phenotypes from dynamic observations.

We will review the theoretical foundations of slow mode identification using transfer operators (illustrated with stochastic and chaotic toy models), and then demonstrate their applicability to real-world data, including posture dynamics in C. elegans and zebrafish.

SOE 2: Focus Session: Physics of Behavior (joint session SOE/DY)

Organizers: Greg Stephens (Vrije Univ. Amsterdam), Pawel Romanczuk (HU Berlin)

Physics has made important contributions to the remarkable progress in characterizing the molecules, cells, and circuits that generate natural behavior. Yet our understanding of behavior at the scale of the whole organism and in ecological and social contexts remains significantly less advanced. Even in simpler organisms, natural behavior is complex, requiring new tools for measurement (often through novel imaging), analysis, and theoretical insight. The emerging field of the physics of behavior addresses this gap by seeking to quantitatively characterize complex behavior in naturalistic settings. This focus session will highlight recent advances at the intersection of physics, neuroscience, biology, and social sciences with contributions from both theorists and experimentalists.

Time: Monday 9:30–12:45 Location: GÖR/0226

Invited Talk SOE 2.1 Mon 9:30 GÖR/0226
Memory and equilibrium in collective animal behaviour — •Thierry Mora — Ecole normale supérieure and CNRS, Paris, France

Some animal groups behave in a highly coordinated way, reminiscent of ordered phases in physics. However, animals are also heterogeneous, have memory, and operate out of equilibrium. I will present recent attempts at modeling the complex dynamics of social groups of mice interacting freely in a controlled environment. I will then assess how far from equilibrium collective behaviour might be, both in recordings of real bird flocks and in flocking models.

SOE 2.2 Mon 10:00 GÖR/0226
Spin-Waves without Spin-Waves: A Case for Soliton Propagation in Starling Flocks — •Andrea Cavagna — Institute for Complex Systems, Rome, Italy

Collective turns in starling flocks propagate linearly with negligible attenuation, indicating the existence of an underdamped sector in the dispersion relation. Beside granting linear propagation of the phase perturbations, the real part of the frequency should also yield a spin-wave form of the unperturbed correlation function. However, new high-resolution experiments on real flocks show that underdamped traveling waves coexist with an overdamped Lorentzian correlation. Theory and experiments are reconciled once we add to the dynamics a Fermi-Pasta-Ulam-Tsingou term.

SOE 2.3 Mon 10:15 GÖR/0226
Modelling filamentous fungal growth — •Pascal Klamser[1], Carlos Aguilar-Trigueros[2] und Dirk Brockmann[1] — [1]Technische Universität Dresden, Dresden, Germany — [2]University of Jyväskylä, Jyväskylä, Finland

The growth of a filament forming fungi is mesmerizing and a great example of an organism that forms a transport network and explores its environment for nutrients. While recent research shows how nutrients and other compounds are transported through the network, we will focus on a transport-agnostic model to explore the possible ways of how the tip of a filament can choose its growth direction. We assume a purely external communication via the diffusion of enzymes released by the filaments and can recreate a wide range of phenotypes. We compare it with experiments by estimating the hierarchical structure of the network from microscopic images.

15 min. break

SOE 2.4 Mon 10:45 GÖR/0226

Understanding how movement behaviors shape animal encounters and their ecological consequences — •Anudeep Surendran — Helmholtz-Zentrum Dresden-Rossendorf, Görlitz, Germany

Encounters between individuals underlie key ecological processes such as predation, mating, and disease transmission, making encounter rates a direct link between individual movement behavior and population-level outcomes. We investigate how two common features of animal movement-directional persistence and range residency-jointly shape encounter rates. Using the Ornstein Uhlenbeck with foraging (OUF) model, which integrates these two properties of animal movement, we derive exact analytical expressions for encounter rates and show that, for range-resident animals, the effect of persistence depends strongly on the degree of home-range overlap. Based on this theoretical result, we then introduce a new encounter-based metric that quantifies the spatial organization of home ranges at scales relevant to animal encounters. We finally apply this metric to movement data from lowland tapirs (Tapirus terrestris) in Brazils Pantanal region, and find a significant level of home-range spatial segregation that is consistent with the solitary behavior of this species.

SOE 2.5 Mon 11:00 GÖR/0226

Composite and combined games in evolutionary dynamics in finite populations — Henry Brooks, Suzannah Gebbett, and •Jens Christian Claussen — University of Birmingham, UK

Evolutionary game theory connects dynamics to strategy by assuming few behavioral strategies, modeling costs and benefits from interactions via a payoff matrices, then casting these into replicator equations (in infinite populations) resp. stochastic processes (in finite populations) which comprise a "physics of behaviour" model of the collective decision dynamics (which may include cyclic oscillations). We build on previous results (PRL 95, 238701 and PRL 100, 058104 and subsequent) and discuss combinations of 2- and 3 strategy games in the context of different replicator dynamics, and stochastic processes derived from agent interaction models. We demonstrate how the previous concepts of drift reversal - how an attracting fixed point resulting from a Hopf bifurcation loses stabilty below a critical population size, applies to the combined games.

SOE 2.6 Mon 11:15 GÖR/0226

A reversal in agent preference reveals partial segregation in the Schelling model — •Maksim Prusakov and Dirk Brockmann — Center Synergy of Systems, TUD Dresden University of Technology, Dresden, Germany

The Schelling model is one of the most famous and seminal models used to describe spatial segregation in social systems. We introduce a small modification to the basic rules of the model: instead of avoiding locations with too many neighbors of a different type, agents now seek places with a high proportion of same-type neighbors. Although this change may seem minor, it leads to qualitatively different behavior. For certain parameter values the system enters an unexpected and new partial-segregation phase, where macroscopically stable segregated clusters coexist with mixed, dynamically active regions.

We construct the phase diagram across tolerance and density values and characterize all macroscopic regimes of the model. The partial-segregation phase emerges robustly across different neighborhood sizes, lattice geometries, and numbers of agent types, which suggests that this behavior follows from the modified preference rule itself rather than from microscopic implementation details. To complement these results, we develop a theoretical framework that describes the stability conditions of the observed phases, with particular attention to the mechanisms that sustain partial segregation. Ultimately, our findings show that even a minor change in the type of local preference can generate fundamentally new collective behavior within Schelling-type models.

SOE 2.7 Mon 11:30 GÖR/0226

Emergence of power-laws and the uncertainty principle in human contact duration — •Jun Sun — GESIS - Leibniz Institute for the Social Sciences, Cologne, Germany

Consider the mechanism underlying human contact duration distributions as an aggregate effect of time-homogeneous processes, where the persistent probability of a contact (pairwise or higher-order) is drawn from a distribution but remains constant during its lifetime (Starnini et al., 2013). I propose a thermodynamic interpretation of the model, in which the persistent probability of a contact is mapped to a negative log-energy, identifying time as the inverse temperature, and the duration distribution as the partition function. I prove that under mild conditions, the contact duration distribution exhibits a power-law with potential cutoffs, a phenomenon commonly observed in empirical data. Such distributions are special in the thermodynamic framework as they have constant specific heat capacity, which corresponds to both the power-law exponent and the effective degrees of freedom. When contact agents act independently, the degrees of freedom equal the contact order. Behavioral correlation between agents reduces the effective degrees of freedom (therefore also the power-law exponent). Finally, I establish an uncertainty relation between time and persistent probability, revealing a fundamental limit within which contact durations can be characterized. Unlike the once-controversial notion of temperature fluctuation, the uncertainty of time in contact data is well-defined.

15 min. break

SOE 2.8 Mon 12:00 GÖR/0226

Wired differently: Individual-level Adaptive Belief Networks — •Peter Steiglechner, Victor Møller Poulsen, Mirta Galesic, and Henrik Olsson — Complexity Science Hub, Vienna, Austria

Our beliefs about political issues are not independent; they are embedded within interconnected belief systems. Models such as the Networks of Beliefs (NB) theory (Dalege et al, 2025) formalise how individuals adjust their beliefs to reduce dissonance, and study how this leads to polarisation or consensus. In these models, the relations between beliefs are static, and the same belief network structure is assumed across individuals. This overlooks that perceived dissonance and belief relations can differ across individuals. And such heterogeneity in belief system structures can affect how individuals respond to external pressures or interventions, such as economic shocks or political scandals. We extend NB theory by allowing belief networks to evolve over time, shifting the focus from dynamics of belief content to the co-evolution of content and structure. In simulations of the model, individuals start with identical belief networks, but their structures diverge, producing stable disagreement between individuals. External events, inducing temporary pressure on a single belief, triggers lasting belief changes in some individuals (compliant), but only temporary or no changes in others (resilient and resistant), regardless of the strength of the pressure. Our model offers an illustrative and endogenous explanation of such asymmetries in responses to external events without requiring traits such as stubbornness, motivated cognition or identity biases.

SOE 2.9 Mon 12:15 GÖR/0226

Critical Transitions of Reinforcement Learning Dynamics in Social Dilemmas — •Balakrishna Prabhu B N and Wolfram Barfuss — Center for Development Research(ZEF), University of Bonn, Germany

Understanding how cooperation emerges and persists among self-interested agents remains a crucial question in the human, animal, and machine behavioral sciences. Specifically, the aspect of the timescales required to reach a cooperative outcome has received little attention.

While the field of equilibrium game theory has addressed the possibility of cooperative outcomes, it offers little insight into how agents select and reach these equilibria, or the timescales required to do so. Evolutionary game theory and reinforcement learning have addressed some of these questions, but are yet to examine the temporal aspects of strategy adaptation and the critical transitions that occur with changes to basic payoff structures.

In this work, we develop a framework based on deterministic dynamics of reinforcement learning to study critical transitions between different social dilemma games. We find that boundaries involving the Chicken game exhibit strong criticality, whereas transitions involving the StagHunt game do not. We also explore convergence times and equilibrium selection and their variations across these boundaries for static and dynamic systems.

By uncovering the dynamic behavior between game transitions, our work lays the foundation for an integrated theory of coupled social-ecological tipping elements.

SOE 2.10 Mon 12:30 GÖR/0226

Statistical mechanics of connected graphs in Scrabble — •Olivier Witteveen and Marianne Bauer — Department of Bionanoscience, Kavli Institute of Nanoscience Delft, TU Delft, Van der Maasweg 9, 2629 HZ Delft, The Netherlands

The crossword-like patterns of tiles in Scrabble form connected graphs of occupied sites on a square lattice. We are interested in describing the ensemble of these Scrabble graphs and comparing them across different languages. To find the most structureless description of Scrabble graphs, we build a maximum-entropy probability distribution; using real tournament data, we adapt a pseudo-likelihood method to the case of connected graphs on a lattice. We find that a maximum-entropy distribution that includes means and pairwise correlations captures the data: it correctly predicts simultaneous square occupation, word-length statistics, and geometric features of the Scrabble graphs, as well as the hierarchy among square types. Finally, we explore how language affects the structure of the Scrabble graphs. We adapt a Scrabble bot to self-play and generate graphs using different lexica. We find that the graphs produced by the bot have lower entropy compared to human players, and that lexica with shorter words yield higher entropy graphs. Remarkably, the pairwise maximum-entropy distribution is almost sufficient to correctly assign Scrabble graphs to their corresponding lexica.

SOE 3: Sustainability: Challenges and Solutions (joint session UP/CPP/SOE)

Accompanying session to Symposium SYSC

Time: Monday 9:30–10:30 Location: MER/0002

SOE 3.1 Mon 9:30 MER/0002

Making a university climate neutral: First experiences from implementing a Climate Protection Strategy at the University of Greifswald — •Christoph G. Hoffmann, Tiemo Timmermann, and Christian von Savigny — University of Greifswald, Greifswald, Germany

With a resolution of its Academic Senate, the University of Greifswald has in 2021 set the goal to achieve climate neutrality by the end of the decade.

While the aim of achieving climate neutrality within a few years is expectedly ambitious, a university as a bigger research institution has also a unique combination of knowledge to achieve it. This has already led to synergies from which particularly the teaching in the environmental subjects can benefit due to "home-made" practical experiences. This makes the whole University a living lab, in which the opportunities but also challenges of necessary transformations can be explored in an assessable setting.

Therefore, also the environmental physics group aims at contributing to and benefiting from this process. While our group is originally focused on basic atmospheric research, we cover a broader range of environmental physics topics in teaching, which overlap with the needs of the transformation process.

In this talk, we will give a short overview of the Climate Protection strategy of the University of Greifswald before we show some examples from our own work regarding the energy consumption of buildings.

SOE 3.2 Mon 9:45 MER/0002

Life Cycle Assessment practices for PV technologies: systematic literature review — •Zeena Patel — Technische Universität Ilmenau

In response to the growing importance of sustainability in solar energy development, this study addresses critical gaps in the application of Life Cycle Assessment (LCA) to photovoltaic (PV) technologies. A systematic review of 48 recent LCA studies across first-, second-, and third-generation PV systems was conducted to evaluate current practices, identify methodological inconsistencies, and highlight emerging trends. Despite increasing research interest and technological diversification, substantial variability exists in the definition of functional units, system boundaries, and impact categories, which hinders comparability and reproducibility. The widespread reliance on secondary databases and the limited use of primary, site-specific data further constrains the accuracy of environmental impact assessments. Additionally, the underutilization of Life Cycle Costing (LCC) and inconsistent application of sensitivity analyses reveal significant gaps in comprehensive sustainability evaluation. To advance the field, this study proposes standardization of LCA methodologies, improved data transparency, and expansion of impact categories beyond global warming potential to include toxicity and resource depletion. These measures are essential for enhancing the robustness, reliability, and policy relevance of PV LCA studies, thereby supporting sustainable innovation and deployment in the solar energy sector.

SOE 3.3 Mon 10:00 MER/0002

Electrochemical Modeling of SOFCs with Emphasis on Microkinetic and Anode Overpotential — •Iram Gul[1], Gabriela Soffiati[2], and Thiago Lopes[3] — [1]Research Center for Greenhouse Gas Innovation, University of São Paulo (USP), 05508-030, São Paulo * SP, Brazil — [2]Institute of Physics (IFUSP), University of São Paulo, Universidade, R. do Matão, 1371 - Butantã, São Paulo - SP, 05508-090 — [3]Research Center for Greenhouse Gas Innovation, University of São Paulo (USP), 05508-030, São Paulo * SP, Brazil

This study investigates Solid Oxide Fuel Cells (SOFCs) using a CO/H fuel mixture, focusing on thermodynamics, mass transport, and electrochemical kinetics. Thermodynamic properties such as heat capacity, enthalpy, entropy, and Gibbs free energy were analyzed across 600-800°C using MATLAB simulations. The Dusty Gas Model (DGM) revealed key mass transport behaviors in the anode, while Density Functional Theory (DFT) using VASP provided insights into surface reaction mechanisms. A microkinetic model examined the impact of anode overpotential on reaction kinetics and cell performance. Results show that higher temperatures improve mass transport and reduce Ohmic losses but slightly decrease the thermodynamic driving force. This multi-scale model enhances our understanding of SOFC behavior and offers a basis for improving fuel cell efficiency and material performance.

SOE 3.4 Mon 10:15 MER/0002

Thermal stability of ceria-zirconia oxides(CeZrO4) nanoparticles using combustion synthesis for the CO oxidation and NOx reduction — •Hamza Mohamed — IMMM, UMRS 6283 CNRS, Le Mans Université, Bd O. Messiaen, 72085 Le Mans Cedex 09, France

The study presents a green synthesis approach for fabricating ceria-zirconia oxide nanoparticles (CeZrO4 NPs) using the solution combustion synthesis method. The synthesized CeZrO4 nanoparticles were characterized using various sophisticated instruments and methods to determine their detailed properties. The UV-Vis spectra showed a characteristic absorbance peak at 242 nm and a band gap (Eg) of 3.05 eV. Simultaneously, Fourier transform infrared spectra of CeZrO4 NPs displayed bands at 418 cm-1, 991 cm-1, 1382 cm-1, 1658 cm-1, 2306 cm-1, 3288 cm-1, and 3643 cm-1, which indicates the presence of phytochemicals that facilitate the reduction and stabilization of CeZrO4 NPs. The major peaks for cubic CeZrO4 NPs were obtained with a crystalline size of 9.6 nm by X-ray diffraction. The microscopic analyses revealed irregular, ovoid, and aggregated morphologies with sizes ranging from 3 to 10 nm. The XPS analysis revealed the existence of Ce3d, Zr3d, C1s, and O1s states with their corresponding atomic percentages. Therefore, this investigation focuses on synthesizing catalysts that demonstrate both thermal stability and high catalytic activity for the oxidation of CO and the reduction of NOx.

SOE 4: Poster Session

Time: Monday 18:00–21:00 Location: P4

SOE 4.1 Mon 18:00 P4

Artificial "Minimal" Intelligence in a Decentralized Mechanical System — •Alex Leffell and Manu Prakash — Stanford University, California, USA

Computation is not exclusive to neurons or transistors. Simple, aneural organisms like Placozoa exhibit complex behaviors, demonstrating that intelligence can arise from non-neuronal physical dynamics. We model these organisms as Phased Active Elastic Sheets (PhAES) – networks of coupled active oscillators that compute via the dynamics of their vibrational modes. This approach builds on established work in both physical learning and active solids and extends it to understand animal behavior. Using both in-silico and robophysical models, we show that this system can perform complex behaviors like gradient climbing without any implicit memory and purely mechanical communication between cells. This perspective offers a direct path towards a new class of computational materials that physically embody sensing, actuation, and learning. Such systems would bridge the gap between rigid, centrally-controlled robots and task-specific soft matter, fundamentally expanding our notions on the physical basis of intelligence.

SOE 4.2 Mon 18:00 P4

Validating diffusion-based dimensionality reduction of political regimes: conflict and child mortality benchmark — •Paula Pirker-Diaz[1], Radost Waszkiewicz[1], Matthew Wilson[2], and Karoline Wiesner[1] — [1]University of Potsdam — [2]University of South Carolina

Political regime indices such as the Electoral Democracy Index (EDI) are widely used for measurement and policy analysis, yet their additive aggregation rules can obscure nonlinear relationships among regime indicators. In earlier work, we showed that a subset of EDI components lies on a low-dimensional nonlinear manifold recovered with the Diffusion Map method [1]. Here we introduce a new one-dimensional regime index by fitting this manifold, identifying the latent dimension along which regime features co-vary most strongly while preserving their nonlinear structure. The resulting index parallels the EDI's characterization of democracies but produces a different ordering among autocracies. By varying the smoothness penalty, we identify the indicators whose contributions to the latent structure remain most stable, providing a robustness-based measure of their relevance. The new index improves the resolution of intra-regime conflict onset probability and child mortality relative to the EDI, with the largest gains among autocratic regimes that the manifold distinguishes more effectively. These findings reinforce that political regimes lie on a nonlinear low-dimensional manifold identified by diffusion methods, which capture social and political variation more effectively than linear aggregation rules. [1] Pirker-Diaz et al., RSOS (2025)

SOE 4.3 Mon 18:00 P4

Realizable Circuit Complexity: Embedding Computation in Space-Time — •Benjamin Prada and Ankur Mali — University of South Florida, Tampa, FL

Parallel computation is typically modeled as a process carried out by abstract machines that ignore the constraints of physical reality. Although the evolution of real-world systems may be mapped to these abstractions, reverse translation is almost always impossible; most computations cannot be simulated in real-time by any device obeying finite propagation speed, bounded volume, or finite entropy. To remedy this discongruity between computational and physical theory, we introduce a framework of *realizable circuits* $\mathbf{RC}_d$ that incorporates a d-dimensional spatial embedding directly into the computation model. The key is that information must cross geometric boundaries at a finite rate: fine-grained entropy flow through a $(d-1)$-dimensional boundary limits the number of independent bits that can be transformed or erased within a d-dimensional region. This yields physically motivated lower bounds on parallel depth and communication, connecting known theoretical and empirical results such as Landauer's principle and Rent's rule. Although the framework is general, we illustrate its usefulness by analyzing modern neural architectures (e.g., transformers and recurrent networks), whose parallel speedups are similarly constrained by entropy flux through bounded interfaces. The resulting theory offers a physics-aligned perspective on the fundamental limits of parallel computation, independent of any specific classical or quantum computing substrate.

SOE 4.4 Mon 18:00 P4

Dynamics of Behavioral Contagion in Human and Artificial Agent Collectives: A Drift-diffusion Simulation Study — •Maryam Karimian[1,2] and Pawel Romanczuk[1,2] — [1]Institute for Theoretical Biology, Department of Biology, Humboldt-Universität zu Berlin, 10115 Berlin, Germany — [2]Science of Intelligence, Research Cluster of Excellence, Berlin, Germany

Behavioral contagion, the spread of behavior within a group, is a central topic in cognitive and collective behavior research. Prior work has either relied on first-person perspective that overlook dynamic social structure or on idealized collective models that neglect individual decision processes. To bridge this gap, we use an extended drift-diffusion model to simulate virtual-reality (VR) experiments, integrating cognitive mechanisms with group-level dynamics. We model agents' decision-making processes, responding to uncertain environmental signals, and influencing one another through an increment drift-diffusion process. Decision states evolve based on accumulated environmental evidence and socially conveyed information. Social information is derived from visually grounded interaction networks capturing first-person sensory constraints shaped by distance and occlusion. These networks are implemented as weighted, directed graphs modulated by group size and density. Using controlled experimental data, we parameterize the model and generate testable predictions on decision dynamics across different environmental and social conditions, highlighting how visual network properties shape vision-mediated contagion and related cognitive processes such as selective attention.

SOE 4.5 Mon 18:00 P4

Optimal transport with constraints: from mirror descent to classical mechanics — •Abdullahi Ibrahim[1,2], Michael Muehlebach[2], Caterina De Bacco[2], and Dirk Brockmann[1] — [1]Center Synergy of Systems, Dresden University of Technology, Dresden, Germany — [2]Max Planck Institute for Intelligent Systems, Cyber Valley, Tuebingen 72076, Germany

Over the past decades, a variety of transportation systems have been successfully modelled using optimal transport (OT), from biological networks as leaf venation, to engineering networks as urban transportation. In this context, adaptation equations that describe how conductivities, flows and pressure potentials evolve interdependently to consolidate into an optimal network structure. This has been used extensively to study a variety of transportation scenarios, and it has been shown to explain with a high degree of similarity observed on real networks. However, current approaches based on adaptation equations suffer from not considering constraints (beyond standard ones like conservation of mass and positivity) as part of the general framework. As a result, networks output from these models can be unrealistic in practice. We address this flaw by proposing a general framework powerful enough to accommodate nonlinear and nonconvex constraints in OT problems. Our approach follows a physics-based perspective on including constraints by leveraging the principle of d'Alembert-Lagrange from classical mechanics. This leads to a sparse, local and linear approximation of the feasible set leading in many cases to closed-form updates.

SOE 4.6 Mon 18:00 P4

GPU-Parallel Load-Flow Solvers with Low-Rank Updates for Contingency Analysis and Topology Optimization — •Marc Hunkemöller[1,2], Nico Westerbeck[3], Lars Schewe[4], and Dirk Witthaut[1,2] — [1]Forschungszentrum Jülich, Institute of Climate and Energy Systems – Energy System Engineering (ICE-1), 52428 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, Köln, 50937, Germany — [3]University of Edinburgh, School of Mathematics, Peter Guthrie Tait Road, Edinburgh, EH9 3FD, UK — [4]Elia Group, Boulevard de l'Empereur 20, 1000 Brussels, Belgium

Power-flow simulations based on the Newton-Raphson method are key tools for transmission system operators. GPUs may accelerate these computations and thus enable fast contingency analysis and new applications such as transmission topology optimization, which are increasingly important for integrating large shares of renewable energy and reducing dependence on fossil fuels. However, parallelization on GPUs is challenging, as the treatment of different topologies does not align well with the "Single Instruction, Multiple Data" paradigm. We present a GPU-parallel AC load-flow solver designed to overcome the difficulties introduced by changing sparsity patterns in the Jacobian matrix when the network topology varies. Our approach uses low-rank updates to separate the Jacobian's dependence on the network structure from its dependence on the system state, allowing topology changes to be incorporated efficiently. In combination with iterative linear solvers, we explore different update orders and strategies to identify stable and fast solver configurations suitable for large sets of topology scenarios.

SOE 4.7 Mon 18:00 P4

Modeling Predator-Prey Encounters via Interacting Ornstein-Uhlenbeck Motions — •Zihao Liu and Ricardo Martinez-Garcia — Helmholtz-Zentrum Dresden-Rossendorf

Most population dynamics models assume well-mixed and independent individuals. However, many animals anchor their movement around key resources such as food, water, or shelter, a behavior well captured by Ornstein-Uhlenbeck home-range dynamics. Previous work has shown that incorporating home-range behavior already leads to substantial deviations in encounter rates from classical predictions. In this study, we further relax the assumption of independence by introducing an explicit attractive interaction from the predator to the prey. Using analytical approximations and individual-based simulations, we explore how this interaction reshapes the encounter landscape across different home-range sizes, spatial separations, force magnitudes, and interaction ranges. We also discuss how small changes in individual movement behavior may influence group-level dynamics, with possible implications for foraging efficiency, spatial clustering, and coexistence conditions.

SOE 4.8 Mon 18:00 P4

Inference of network structures from partial observations — •Matthias Klaus[1,2], David Dahmen[1], and Moritz Helias[1,2] — [1]Institute for Advanced Simulation (IAS-6), Jülich Research Centre, Jülich, Germany — [2]Department of Physics, Faculty 1, RWTH Aachen University, Aachen, Germany

Today's recording techniques for neural activity allow one to access finite time windows of a few hundred to thousands of neurons. Since they are embedded in strongly connected networks of 10^5 neurons, the recorded data will be considerably influenced by the structure of these unobserved parts. Theoretical descriptions of the problem often assume spatial and temporal homogeneity across the system, i.e. that structure and activity of the entire network, on a statistical level, are close to the recorded part.

Here we model this statistical homogeneity by the variances of connectivity and of a globally independent driving white noise. Estimates for these parameters exist from prior experiments. Consequently, we use a Bayesian approach to obtain a posterior for the local connectivity by conditioning on the locally recorded activity. The theory involves a marginalization over unobserved activity, which is exact for a linear network with Gaussian activity. This condition can be relaxed by reasonably assuming a large network and applying dynamic mean-field theory (Sompolinsky, Crisanti, Sommers 1988; Schuecker, Goedeke, Helias 2018). We find that reconstruction of local connectivity is possible if the influence from unobserved parts reduces to a colored noise whose statistics is estimated correctly.

SOE 4.9 Mon 18:00 P4

A Conceptual Model for Temperature dynamics in the Climate System — •Fatemeh Aghaei and Holger Kantz — Max Planck Institute for the Physics of Complex Systems

we propose a simple conceptual model for tipping of the Earth's atmospheric dynamics due to feefback loops from global mean temperature on the release of greenhouse gases by natural processes. The model shows that the strength of this feedback is a relevant parameter which determined the speed of climate change after passing through a tipping point, to be extracted from earth system models. Also, we show that by data analysis, it might be possible to reconstrict the functional form of the feedback process. We illustrate both by the analysis of model data.

SOE 5: Network Science

Time: Tuesday 9:30–10:30 Location: GÖR/0226

Invited Talk SOE 5.1 Tue 9:30 GÖR/0226

Network Science in Criminology: Insights from Empirical Case Studies — •Masarah Paquet-Clouston — University of Montreal, Montreal, Canada

Network science has become a central tool in criminology, offering powerful ways to model illicit relationships and hidden organizational structures. This presentation draws on three empirical case studies that apply network-based methods to real-world criminological problems: mapping how cybercrime forum users connect with specific topics, tracing money flows in illicit cryptocurrency transactions, and identifying links among corporate secrecy vehicles.

These examples highlight both the analytical potential of network-based approaches and the methodological challenges inherent to criminological data. I will conclude by identifying open research questions that advances in related fields, such as complexity science, could help address.

SOE 5.2 Tue 10:00 GÖR/0226

Collective decision making with biases - Role of network topology — Yunus Sevinchan[1], Petro Sarkanych[2], Archili Sakevarashvili[1], Yurij Holovatch[2,3], and •Pawel Romanczuk[1] — [1]Institute for Theoretical Biology, Dept. of Biology, Humboldt Universität zu Berlin — [2]Yukhnovskii Institute for Condensed Matter Physics of the National Academy of Sciences of Ukraine, Lviv, Ukraine; 𝕃4 Collaboration and Doctoral College for the Statistical Physics of Complex Systems, Lviv-Leipzig-Lorraine-Coventry, Europe — [3]Complexity Science Hub, Vienna, Austria

The accuracy of collective decision-making in groups depends on a complex interplay of factors, including prior information, biases, social influence, group composition, and the structure of the interaction network. In this work, we study a spin-type model in which interactions are mediated through a social field generated by an agent's neighbors, allowing for heterogeneous individual preferences. Building on previous results [1], we examine how network topology affects consensus formation. We show that, unlike the Ising model, the social-field model exhibits fundamentally similar behavior on both scale-free and Erdős-Rényi networks, a result that can be attributed to weaker hub-hub interactions. Finally, we investigate the extent to which a strongly biased minority can dominate the collective decision, even in the presence of an oppositely biased majority.

[1] Sarkanych *et al*, Phys Biol 20 (2023); Sarkanych *et al*, Cond Matt Phys 27 (2024); Sevinchan *et al*, Phys Rev Res 7 (2025)

SOE 5.3 Tue 10:15 GÖR/0226

Operational time and criticality in physics co-authorship networks — •Pouria Mirelmi[1] and Haiko Lietz[2] — [1]Leiden University, Leiden, The Netherlands — [2]GESIS – Leibniz Institute for the Social Sciences, Cologne, Germany

Many real-world complex networks display either fractal or small-world structure, but rarely both. Prior work explains this incompatibility through static architectural constraints: fractality emerges from critical branching trees, whereas small-world structure requires supercritical expansion supported by long-range shortcuts. Here we show that this dichotomy is not merely structural but dynamical. Using more than a century of APS co-authorship data, we construct a sequence of network time slices by tuning aggregation to the percolation transition. Measuring a set of macro-level parameters – including percolation observables and small-world indicators – we find that all scale as power laws with the networks' distance from criticality. Networks remain fractal near criticality but acquire small-world shortcuts only when aggregated beyond the critical point. We further show that the critical time scale emerging from this aggregation procedure constitutes an operational time to which the system self-organizes: citation avalanches obey dynamical scaling theory only when defined in this intrinsic time. These results indicate that static analyses are insufficient whenever the evolutionary time scale of a network is empirically accessible. A dynamical scaling framework is required to correctly identify and characterize critical and supercritical network states.

SOE 6: Mobility, Traffic Dynamics, Urban and Regional Systems

Time: Tuesday 10:45–12:45 Location: GÖR/0226

SOE 6.1 Tue 10:45 GÖR/0226

Percolation on the "urban influence" field: analyzing Europe's urban fabric — •Renan Lucas Fagundes[1] and Diego Rybski[1,2] — [1]IOER, Dresden — [2]CSH, Vienna

We investigate the connectivity of urban settlements using the concept of level-set percolation (LSP). Therefore, we introduce a notion of urban influence, quantifying the impact of the presence of urban settlements in their surroundings. To be specific, we define a power-law field over the urban settlements in Europe in 2018. This field can be understood in a similar fashion as 2D Gaussian Random Field but with a power-law. We find a relationship between the level where the second largest cluster reaches a maximum – an indicator of the percolation transition – and the imposed field-exponent. The exponential slope of the relation correlates with the size of the country. We speculate that the critical behavior of the field is being driven by the spatial organization of the urban structure.

SOE 6.2 Tue 11:00 GÖR/0226

Global settlement percolation: estimating critical distances — •Diego Rybski — IOER Dresden

Cities and settlements can be understood as percolating systems. We apply spatial clsutering, where any two items belong to the same cluster if their Euclidean distance is smaller than a threshold. Varying this threshold, at a critical distance a transtion occurs where a giant cluster emerges – resembling a percolation transition. We systematically analyze high-resolution data on the global scale and estimate this critical distance for various spatial units. We find that the critical distance is complementary to other geographical indicators. Our estimates can be of use for down-stream research.

SOE 6.3 Tue 11:15 GÖR/0226

Scaling laws beyond cities — •Yiwei Yang[1,2], Benedikt Grammer[1], Rafael Prieto-Curiel[3], David Frantz[4], Helmut Haberl[1], and Dominik Wiedenhofer[1] — [1]BOKU University, Vienna, Austria — [2]MPG-DLU, Jena, Germany — [3]CSH, Vienna, Austria — [4]Trier University, Trier, Germany

Urban scaling laws reveal that larger cities tend to be more resource-efficient and innovative, but the standard framework has two well-known limitations: (1) the one-city-one-value approach assumes that the entire urban area is the only meaningful unit of analysis; (2) carefully delineated city boundaries artificially divide what is in fact a continuous human settlement system. These issues motivate examining scaling relationships within cities and across the rural-urban continuum. We hypothesize that fine-scale properties, in particular infrastructure-related attributes tied to fractal urban form, scale with population across the full fabric of human settlements. We test this using high-resolution gridded maps for the contiguous United States, analyzing how built-environment material stocks, service provisioning, and operational greenhouse gas emissions scale with population at the settlement-cell level. Through stepwise empirical tests, we not only demonstrate that scaling is present at fine spatial scales within human settlements, but also identify three important features of intra-settlement scaling. Our findings reframe the view that the city is the sole scale at which scaling laws arise, reveal pronounced intra-settlement heterogeneities, and offer practical implications for the analysis and planning of sustainable settlement development.

15 min. break

SOE 6.4 Tue 11:45 GÖR/0226

Higher-order interactions yield synergistic infrastructure backbones — •Christoph Steinacker[1], Henrik Wolf[2], Marc Timme[1], and Malte Schröder[1] — [1]Chair of Network Dynamics, Center for Advancing Electronics Dresden (cfaed) and Institute of Theoretical Physics, TUD Dresden University of Technology, 01062 Dresden, Germany — [2]AMOLF, Amsterdam, Netherlands

Infrastructure networks essentially underlie human mobility across all modes of transport. Higher-order interactions among different network elements impact network performance as they generically induce modified usage at every element across the network. Here, we consider such higher-order interactions to reveal and quantify the synergies between different link upgrades in transport networks. While network expansion strategies based on first-order, individual link importance result in scattered, disconnected networks, sets of pairs of mutually synergistic links automatically form connected backbones of infrastructure networks. We illustrate the approach with a perturbed utility route choice model for bicycle traffic on empirical urban street networks. Our results not only provide a novel theory of evaluating complex transport networks beyond individual link importance, they may also help to guide strategic network planning in practice.

SOE 6.5 Tue 12:00 GÖR/0226

Where2Share–Complex system predictions of ridepooling potential in Germany — Philip Marszal, Felix Jung, Marc Timme, and •Malte Schröder — Chair of Network Dynamics, Center for Advancing Electronics Dresden (cfaed) and Institute of Theoretical Physics, TUD Dresden University of Technology, 01062 Dresden, Germany

Complex system modeling often provides general insights about similar systems in vastly different settings by identifying the key mechanisms driving their dynamics. Here, we demonstrate how this perspective may help avoid many individual case studies and expensive pilot projects when planning on-demand ridepooling services that promise to reduce the number of cars on the road and cut back emissions by dynamically combining trips of multiple users in the same vehicle. By exploiting the transferability of complex system models of ridepooling based on a small number of cornerstone parameters, we built an open-data framework to estimate the potential reliability and efficiency of these services. We apply our framework to create a map of the ridepooling potential in Germany, quantifying key performance and operating parameters of ridepooling services across more than 400 vastly different service areas. Our framework is easily applicable to other regions and provides valuable insights about the influence of network topology, fleet size, and demand structure on the potential performance of ridepooling services. The results presented here may help focus the planning of ridepooling services by informing decision-making from the earliest point.

SOE 6.6 Tue 12:15 GÖR/0226

Self-organized co-existence of fixed and flexible pooling routes — •Nora Molkenthin, Karolin Stiller, and Alexander Schmaus — Potsdam Institute of Climate Impact Research (PIK)

Shared pooled mobility describes a diverse class of nonlinear, nonlocally coupled transport models, which give rise to rich, yet currently not fully understood dynamics. In this system we have observed the spontaneous emergence of periodic trajectories in passenger-optimized as well as fleet-distance optimized ride-pooling simulations at moderate to high request densities. Despite the uniformly distributed origin-destination pairs as driving input, we find partially periodic routes for some parameter and network choices, while at others, all routes remain unstructured. This dynamical symmetry breaking from unstructured to partially periodic trajectories occurs as the request load increases. These findings suggest a new class of chimera-like behaviour in real-world-inspired, spatially embedded, non-oscillatory systems. This finding has a natural interpretation as a regime of emergent co-existence between shared pooled mobility and line-based public transport, even without policy intervention.

SOE 6.7 Tue 12:30 GÖR/0226

Pulses, waves, and chaos in migration dynamics — Niraj Kushwaha[1], Woi Sok Oh[2], and •Edward Lee[1] — [1]Complexity Science Hub, Vienna, Austria — [2]University of Waterloo, Waterloo, Canada

Decisions to migrate depend on others' decisions. Dependence can produce both stable long-term trends and sudden transitions, which appear in data but could be the result of either exogenous drivers or of endogenous dynamics. We propose a simple migration model that accounts for social influence and individual heterogeneity in decisions to migrate. The minimal model displays hysteresis, waves, and chaotic-like regimes. This occurs in special locations of parameter space, suggesting that migration response to external conditions could be highly dependent on whether the system is poised near or far away from dynamical instability. Conditioning on this distance would be key to determining "causal drivers" of migration. In the context of displacement, for example, this would be relevant for oft-considered correlates like armed conflict and onset of natural disasters. We show how the model aligns with features of migration statistics including from internal displacement and maritime crossings.

SOE 7: Award Session: Young Scientist Award for Socio- and Econophysics (YSA)

Time: Tuesday 14:00–15:30 Location: GÖR/0226

Topical Talk SOE 7.1 Tue 14:00 GÖR/0226
What's that noise? Why does it make a difference? And why am I thinking about it all the time? — •Dirk Brockmann — Center Synergy of Systems, TU-Dresden, Dresden, Germany

Replication is one of the central processes in biological, ecological, evolutionary and, in more subtle ways, also social systems. Unsurprisingly, many dynamical systems designed to describe such phenomena implement replication in one form or another. Some are even labeled as such, for example the replicator equation, a keystone system whose many variants populate ecological and evolutionary modelling with admirable persistence. Despite their conceptual simplicity, replicator systems have a habit of producing surprises and sit at the center of long-standing controversies. One of these is an apparent paradox: the competitive exclusion principle, often a generic hallmark of replicator dynamics, seems fundamentally at odds with the remarkable diversity of species with very similar ecological functions observed in real ecosystems. Nature, it appears, did not read the textbook. Fluctuating environments and, more generally, noise have been proposed as a way out of this dilemma. Yet models that include noise tend to disagree with one another, leaving the puzzle very much alive. In this lecture, I will discuss how noise can affect replication in qualitatively different ways, why it matters which noise you add and how, how this may help us understand coexistence in ecosystems, and why thinking about all this may quietly reshape how we understand cooperation as a pervasive feature of the biosphere.

Presentation of the Award to the Awardee

Prize Talk SOE 7.2 Tue 14:45 GÖR/0226
How things spread: Complexity and criticality of inhomogeneous spreading models — •Laurent Hébert-Dufresne — University of Vermont, Burlington VT, USA — Santa Fe Institute, Santa Fe NM, USA

Models of how things spread often assume that transmission mechanisms are fixed over space and time. However, the transmission of infectious diseases can depend on local human behaviour or quality of the surrounding infrastructure. Likewise, social contagions like the spread of ideas, beliefs, and innovations depend on local norms or culture, and they can lose or gain in momentum as they spread. Diseases mutate and find subpopulations where they can thrive, just as ideas can get reinforced, beliefs strengthened, and products refined. We study the impacts of these mechanisms in spreading and cascade dynamics. Using different modelling tools, we find that complexity and criticality are the norm: Superlinear relationships between exposure and transmission can emerge from linear interactions and power-law distributions with anomalous scaling can be observed away from any critical point.

SOE 8: Networks, From Topology to Dynamics I (joint session SOE/DY)

Time: Wednesday 9:30–11:00 Location: GÖR/0226

Invited Talk SOE 8.1 Wed 9:30 GÖR/0226
Dynamics and Structure in Temporal Networks — •Natasa Djurdjevac Conrad — Zuse Institute Berlin, Germany

Temporal networks are a powerful tool for describing real-world systems in which interactions change over time, such as social contacts or transportation systems. Understanding how these networks evolve is crucial for uncovering the mechanisms that drive system behavior. From a dynamical systems perspective, clustering temporal networks and tracking the dynamics of clusters enables the identification of long-lived structures, metastable states and tipping points. In this talk, I will present recent work on temporal network analysis using random walk-based approaches, with a focus on network clustering and detecting structurally coherent time-periods. These methods provide a natural connection between network science and dynamical systems, relating to transfer operator frameworks and spectral theory. Through examples from synthetic models and real-world datasets, I will illustrate how these tools uncover key patterns and dynamic changes in complex networks.

SOE 8.2 Wed 10:00 GÖR/0226
From Quiescence to Synchrony: Noise-Shaped Dynamics in Coupled Neuronal Systems — •Max Contreras[1,2] and Philipp Hövel[2] — [1]Technische Universität Berlin, Germany — [2]Saarland University, Saarbrücken, Germany

Stochastic fluctuations are usually regarded as promoters of activity in excitable and oscillatory systems, giving rise to phenomena such as coherence resonance. Here, we show that the opposite can occur in the small-noise regime, where noise can inhibit spiking activity in weakly coupled neuronal units. Using a ring of diffusively coupled, oscillatory FitzHugh-Nagumo neurons, we demonstrate how the interplay of noise and coupling strength generates different collective behaviors. We systematically classify the dynamical scenarios by an in-depth time-series analysis that combines multiple, complementary measures. As a result, we are able to automatically identify distinct dynamical clusters in parameter space: quiescent state, noisy synchronization, complete synchronization, and intermittent switching. The presented workflow can be universally applied in coupled oscillator networks and provides a unified framework to study collective dynamics.

15 min. break

SOE 8.3 Wed 10:30 GÖR/0226
Learning collective variables for time-evolving networks — •Sören Nagel, Nataša Djurdjevac Conrad, Stefanie Winkelmann, and Marvin Lücke — Zuse Institute Berlin

We address the challenge of model reduction for time-evolving networks by identifying collective variables for stochastic rewiring processes driven by opinion homophily. [Lücke et al., Phys. Rev. E 109, L022301 (2024); Djurdjevac Conrad et al., Chaos 34, 093116 (2024)].

Utilizing the *transition manifold framework*, we identify a simple consensus measure as a collective variable for an ergodic and a non-ergodic model, and learn the dynamics of the projected system. We show that the learned model reduction can be obtained from the corresponding graphon process in the case of large and not too sparse graphs with uniformly distributed opinions. Our data-driven approach successfully identifies the collective variables in more general cases, highlighting the possibility to study low-dimensional model reductions in systems that have not been understood theoretically.

SOE 8.4 Wed 10:45 GÖR/0226
Time-delayed dynamics in regular networks of Kuramoto oscillators with inertia — •Philipp Hövel[1], Esmaeil Mahdavi[2], Mina Zarei[2], and Farhad Shahbazi[3] — [1]Saarland University, Saarbrücken, Germany — [2]Institute for Advanced Studies in Basic Sciences, Zanjan, Iran — [3]Isfahan University of Technology, Isfahan, Iran

We investigate the complex interplay between inertia and time delay in regular rotor networks within the framework of the second-order Kuramoto model. By combining analytical and numerical methods, we demonstrate that intrinsic time delays – arising from finite information transmission speeds – induce multistability among fully synchronized phase-locked states. Unlike systems without inertia, the presence of inertia destabilizes these phase-locked states, reduces their basin of attraction, and gives rise to nonlinear phase-locked dynamics over specific inertia ranges. In addition, we show that time delays promote the emergence of turbulent chimera states, while inertia enhances their spatial extent. Notably, the combined influence of inertia and time delay produces dynamic patterns reminiscent of partial epileptic seizures. These findings provide new insights into synchronization phenomena by revealing how inertia and time delay fundamentally reshape the stability and dynamics of regular rotor networks, with broader implications for neuronal modeling and other complex systems.

SOE 9: Economic Models

Time: Wednesday 11:30–12:45 Location: GÖR/0226

SOE 9.1 Wed 11:30 GÖR/0226

Macroscopic Stochastic Model for Economic Cycle Dynamics — •Eckehard Schöll[1,2], Sören Nagel[2,3], and Jobst Heitzig[2] — [1]TU Berlin — [2]Potsdam Institute for Climate Impact Research — [3]Zuse Institute Berlin

We present a stochastic dynamic model which can explain economic cycles [1]. We show that the macroscopic description yields a complex dynamical landscape consisting of multiple stable fixed points, each corresponding to a split of the population into a large low and a small high income group. The stochastic fluctuations induce switching between the resulting metastable states, and excitation oscillations just below a deterministic bifurcation. The shocks are caused by the decisions of a few agents who have a disproportionate influence over the macroscopic state of the economy due to the unequal distribution of wealth among the population. The fluctuations have a long-term effect on the growth of economic output and lead to business cycle oscillations exhibiting coherence resonance, where the correlation time is controlled by the population size which is inversely proportional to the squared noise intensity.

[1] S. Nagel, J. Heitzig, and E. Schöll: Macroscopic stochastic model for economic cycle dynamics. Phys. Rev. Lett. 134, 047402 (2025).

SOE 9.2 Wed 11:45 GÖR/0226

Kinetic theory re-examination of the mean-field theory of Santa Fe financial market model — •Taiki Wakatsuki and Kiyoshi Kanazawa — Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

Understanding and accurately modeling the statistical phenomena observed in real financial markets remains a central challenge in econophysics. In particular, the Santa Fe model, where order events occur according to a Poisson process, has been widely used as a verifiable financial market model. Simulation results of the Santa Fe model clearly demonstrate that it can explain the statistical laws of real markets to a certain extent. However, previous theoretical explanations of these statistical laws, which relied on dimensional analysis and mean-field theory, are neither unique nor fully sufficient. Therefore, this study will re-examine the mean-field theory of the Santa Fe model using kinetic theory. This presentation provides a theoretical analysis of the bid-ask spread and reports on its scaling.

SOE 9.3 Wed 12:00 GÖR/0226

Hallmarks of deception in asset-exchange models — •Kristian Blom[1], Dmitrii E. Makarov[2], and Aljaz Godec[3] — [1]Institute of Theoretical Physics, University of Münster — [2]Department of Chemistry, The University of Texas at Austin — [3]Mathematical bioPhysics group, MPI for Multidisciplinary Sciences

Asset-exchange models, such as the Bennati-Dregulescu-Yakovenko money game, have emerged in econophysics as simple models that capture generic features of wealth dynamics. In the BDY game, the wealth of a single player undergoes a one-dimensional random walk. Because the exchange probability of losing and gaining money are equal, one may surmise that this walk is unbiased, but this is not the case: the boundary condition that each player's wealth cannot be negative introduces a loss bias because of the possibility that an exchange partner has zero wealth. This results in an exponential steady-state distribution. Here, we extend the BDY game by introducing probabilistic cheaters that can misrepresent their financial status with a given probability. Cheaters deceive their exchange partners by claiming that they have no money, enabling them to evade potential losses. In a system consisting of honest players and cheaters, we show how cheating alters the transient dynamics as well as steady-state distributions of wealth. We identify a threshold probability for cheating beyond which cheaters accumulate more than half of the total money. Additionally, we show under which conditions cheating becomes beneficial and establish the existence of a critical cheating probability at which the wealth of cheaters undergoes a second-order discontinuity.

SOE 9.4 Wed 12:15 GÖR/0226

Identifying higher order cascading failures in supply chain networks of a national economy — •Jan Fialkowski[1,2], Stefan Thurner[1,2,4], and Shlomo Havlin[3] — [1]Complexity Science Hub, Vienna, Austria — [2]Institute of the Science of Complex Systems, CeDAS, Medical University Vienna, Vienna, Austria — [3]Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel — [4]Santa Fe Institute, Santa Fe, USA

Cascading Failure scenarios are a central concern for the design of complex systems. In financial and economic systems these cascading failures give rise to the notion of systemic risk, where the failure of a single entity leads to large disruptions in the entire system. Exhaustively examining the failure of larger sets of elements is difficult due to computational constraints. Here we study the recently introduced notion of economic systemic risk in national supply chain networks of firm-firm interactions. We use an empirical dataset of the ecuadorian economy, consisting of almost 100.000 firms and more than three million buyer-supplier links. Using a modification of the "Random Chemistry" method we can identify small sets of firms, whose simultaneous failure leads to failure cascades that are larger than would be expected from their individual failure cascades.We compare the final cascade size of the small sets of firms with the sum of cascade sizes of the individual firm failures and find pairs that are up to 260 times more destructive than the individual firms themselves. We also provide a classification of the underlying mechanisms leading to this strong increase of the final cascade size.

SOE 9.5 Wed 12:30 GÖR/0226

Overcoming the Prestige Trap: Modelling the Transition to Community-Led Academic Publishing — •Valentin Lecheval[1,2], Clémence Bergerot[1,3], Valerii Chirkov[1,2], Giuseppe Maria Ferro[4], and Daniel Rubenstein[4] — [1]Department of Biology, Humboldt Universität zu Berlin, Berlin, Germany — [2]Science of Intelligence, Research Cluster of Excellence, Berlin, Germany — [3]Charité-Universitätsmedizin Berlin, Einstein Center for Neurosciences Berlin, Berlin, Germany — [4]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ, USA

The academic publishing industry is dominated by a few for-profit companies, resulting in the corporate capture of a substantial share of public funds that could instead support academia. While alternative publishing models are not lacking–community-led publishers offering diamond open-access, or directing article processing charges towards academic services–they suffer from reduced attractivity compared to their for-profit counterparts, possibly due to first-mover advantages and path-dependent reputational dynamics. Here, we introduce a multi-scale agent-based model depicting the joint dynamics of research groups and journals. The parameters of research groups dictate their preference for journals, weighting various attributes, such as reputation or community services–attributes that can depict for-profit journals, society-based journals, open-access mega-journals or predatory journals. We simulate the model on a wide range of parameters to investigate the conditions leading community-led journals to overcome path-dependent barriers and dominate the publishing landscape.

SOE 10: Networks, From Topology to Dynamics II (joint session SOE/DY)

Time: Wednesday 15:00–15:45 Location: GÖR/0226

SOE 10.1 Wed 15:00 GÖR/0226

Combining machine-learning and dynamic network models for sepsis prediction — •Juri Backes[1,3], Artyom Tsanda[1,2], Tobias Knopp[1,2], Wolfgang Renz[3], and Eckehard Schöll[4] — [1]TU Hamburg — [2]UKE Hamburg — [3]HAW Hamburg — [4]TU Berlin

We enhance short-term sepsis predictions by integrating machine learning techniques like Auto-Encoders and Gated-Recurrent-Units with a dynamical 2-layer network model of adaptive phase oscillators [1] representing the interaction between parenchymal cells (functional organ cells) and the immune system via cytokines. The model trajectories determined by machine learning are used for detection and prediction of critical infection states and mortality. The model-based predictions are compared with those of purely data-based approaches in terms of predictive power and interpretability. To this end we project real high-dimensional medical patient data into the low-dimensional parameter space of the model.

[1] R. Berner, J. Sawicki, M. Thiele, T. Löser, and E. Schöll: Critical parameters in dynamic network modeling of sepsis. Front. Netw. Physiol. 2, 904480 (2022).

SOE 10.2 Wed 15:15 GÖR/0226

Forecasting emergency department visits in the reference hospital of the Balearic Islands: the role of tourist and weather data — •Paride Crisafulli, Tobias Galla, Raul Toral, and Claudio Mirasso — IFISC (UIB-CSIC), Palma de Mallorca, Spain

Accurate forecasting of patient arrivals at emergency departments (EDs) is vital for efficient resource allocation and high-quality patient care. Despite its significance and extensive prior research, certain conditions can significantly impact the accuracy of these estimates. This study investigates the relevance of tourism and weather data alongside traditional calendar and demographic variables in forecasting ED visits in the reference hospital in Palma de Mallorca, a city with significant seasonal population fluctuations due to tourism. Utilizing a machine learning approach, we develop a model that predicts ED visits based solely on exogenous variables. We test three different machine learning algorithms (random forests, support vector machines, and feed-forward neural networks) with four different input combinations, comparing their mean average percentage errors (MAPEs) and prediction horizons.

SOE 10.3 Wed 15:30 GÖR/0226

Beyond Averages: How Disease Severity and Social Structure Interact to Shape Pandemic Dynamics — •Fabio Sartori, Sophia Horn, Sven Banisch, and Michael Maes — Chair of Sociology and Computational Social Science, Karlsruhe Institute of Technology, Karlsruhe

Epidemiological models typically rely on population averages, overlooking behavioral polarization and social structure. We developed a compartmental framework examining how polarization and homophily shape outcomes across mask-wearing, testing, and vaccination interventions. Results reveal intervention-specific effects: polarization benefits masks but harms testing and vaccination. Homophily worsens outcomes for low-infectivity diseases by removing protective barriers, but improves outcomes for highly infectious diseases through protective bubbles. Calibrating with German survey data (n=1,612), homogeneous models showed large errors. Intervention effectiveness depends critically on social structure and pathogen characteristics, not just average compliance.

SOE 11: Polarization

Time: Wednesday 15:45–17:15 Location: GÖR/0226

SOE 11.1 Wed 15:45 GÖR/0226

Accurate mean-field predictions for cognitively grounded social influence dynamics with confirmation bias — •Sven Banisch — Karlsruhe Institute of Technology

Collective opinion formation in human groups is often modeled through cognitively rich agent-based dynamics, yet the resulting high-dimensional systems typically resist analytical treatment. Here we show that a class of cognitively grounded argument-exchange models with confirmation bias admits a low-dimensional and fully tractable mean-field representation. The key idea is to project pairwise agent rules onto an influence response function and then derive a two-compartment mean-field system whose Jacobian separates into a mean mode and a polarization mode. This yields a simple stability test that diagnoses the onset of symmetry breaking. We recover the consensus-to-polarization tipping point and identify a second threshold at which polarized equilibria become fully stable. Across all parameter regimes, the mean-field bifurcation structure accurately reproduces the behaviour of the full agent-based model. Our results provide a general mechanism-level framework for understanding how cognitive biases shape macroscopic opinion patterns, and demonstrate that high-dimensional social influence dynamics can exhibit simple and universal phase-space structure amenable to analytical classification.

SOE 11.2 Wed 16:00 GÖR/0226

Dynamics of ideologically polarized social media users — •Tristram Alexander and Jamie Tyler — University of Sydney, Australia

Social media users have been shown to exhibit different types of behaviour and preference on social media, depending on their ideological position on a left-right axis. This work investigates whether observed differences may be attributed to intrinsic differences in the users, or whether the differences emerge based on interactions in the social media environment.

The study is based on interactions between users on the Twitter/X platform. Users are classified on a left-right scale based on their retweet activity, and placed into categories based on their position on this scale. The reply activity between users is then examined to determine the rates of interaction between the different classes of user. The population of the users in each interaction class is then estimated, based on frequencies of interaction between the classes.

The study finds that users appear to have the same intrinsic behaviour, irrespective of ideological class, but that they behave differently due to the population imbalance between the classes on the platform. This leads right-leaning users to be more active then left-leaning users, which is posited as a reason for greater observed departure rates of right-leaning users from the platform. A model of this interaction behaviour is developed and mapped to the observations. The results of this work may inform the further development of opinion dynamics models.

15 min. break

SOE 11.3 Wed 16:30 GÖR/0226

Campaign-spending driven polarization transition in a double-random field model of elections — •Jan Korbel[1], Remah Dahdoul[1], and Stefan Thurner[1,2,3] — [1]Complexity Science Hub, Vienna, Austria — [2]Medical University of Vienna, Austria — [3]Santa Fe Institute, NM, US

We model bipartisan elections where voters are exposed to two forces: local homophilic interactions and external influence from two political campaigns. The model is mathematically equivalent to the random field Ising model with a bimodal field. When both parties exceed a critical campaign spending, the system undergoes a phase transition to a highly polarized state where homophilic influence becomes negligible, and election outcomes mirror the proportion of voters aligned with each campaign, independent of total spending. The model predicts a hysteresis region, where the election results are not determined by campaign spending but by incumbency. Calibrating the model with historical data from US House elections between 1980 and 2020, we find the critical campaign spending to be ~1.8 million USD. Campaigns exceeding critical expenditures increased in 2018 and 2020, suggesting a boost in political polarization.

SOE 11.4 Wed 16:45 GÖR/0226

Information Saturation in the Political Center Drives the Spread of Extreme Content — •Markus Hofer[1,2], Jan Korbel[2], and Stefan Thurner[1,2,3] — [1]Center for Medical Data Science, Institute of the Science of Complex Systems, Medical University of Vienna, Vienna 1090, Austria — [2]Complexity Science Hub Vienna, Vienna 1030, Austria — [3]Santa Fe Institute, Santa Fe, NM 87501

Although most voters hold moderate opinions, online discourse is increasingly dominated by ideological extremes. To understand this phenomenon, we employ an agent-based model in which post-sharing mediates all opinion dynamics. First, agents filter posts based on ideological distance to update their own opinions. Then they select one of the received posts based on novelty, quantified as the local information-theoretic surprisal. Here we show that empirically consistent opinion distributions with moderate polarization naturally emerge alongside a disproportionate sharing of extreme content. We identify the underlying mechanism as a density-dependent competition for novelty: high post density in the political center leads to information saturation, effectively suppressing surprisal and resharing. In contrast, extreme content maintains high surprisal, increasing its resharing probability. This mechanism explains the heavy-tailed cascade distributions observed on Twitter/X and points toward interventions that reduce the informational novelty advantage of extreme content.

SOE 11.5 Wed 17:00 GÖR/0226

The role of antagonization in political discourse on social media — •Armin Pournaki and Eckehard Olbrich — Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany

Antagonization is a central discursive strategy in political narratives. The creation of an enemy allows for political mobilization through powerful affective mechanisms. It is commonly assumed that social media, through a combination of platform affordances and algorithmic amplification, reward and therefore enhance antagonizing content. However, it is an open empirical question whether the prevalence and nature of antagonization as a discursive strategy depends on the political leaning, or whether different political camps antagonize equally. The present work aims to address those questions by presenting a novel computational approach to systematically extract traces of antagonization from text, including potential targets of antagonization. On a corpus of 1M tweets from the German Twittersphere, we observe a strong prevalence of antagonizing content, confirming common hypotheses by which social media tend to facilitate such discourse. By combining the method with a large-scale estimation of ideological positions of users based on their retweet behaviour, we show that antagonization is significantly more prevalent in the online discourse of right-leaning than of left-leaning actors. Finally, a systematic analysis of the various antagonized targets provides novel insights into how different political factions employ this strategy to mobilize their audience.

SOE 12: Statistical Physics of Politics

Time: Wednesday 17:15–18:00 Location: GÖR/0226

SOE 12.1 Wed 17:15 GÖR/0226

Critical Dynamics govern the Evolution of Political Regimes — •Joshua Uhlig[1], Paula Pirker-Díaz[1], Matthew Wilson[2], Ralf Metzler[1], and Karoline Wiesner[1] — [1]University of Potsdam, Potsdam, Germany — [2]University of South Carolina, Columbia, SC, USA

The emergence and decline of democratic systems worldwide raises fundamental questions about the dynamics of political change. Contrary to the idea of a stable end point of liberal democracy, recent backsliding towards less democratic regimes highlights the non-stationary nature of regime evolution [1]. Here, we analyse the historical trajectories of countries within a two-dimensional regime space derived from the principal components of the Varieties of Democracy dataset [2]. We observe weakly non-ergodic dynamics unfolding in an effective landscape characterised by sparse and shifting basins of stability. Step sizes and waiting times follow heavy-tailed distributions near the critical regime, in which mean values appear to diverge, indicating intermittent and heterogeneous regime change. A continuous time random walk model [3] reproduces the dynamics of the three most recent decades with remarkable accuracy. Together, these results suggest that some aspects of political regime evolution follow universal stochastic principles, while remaining punctuated by unique historical pathways.

[1] P Pirker-Díaz et al., R Soc Open Sci. 12, 250457 (2025) [2] K Wiesner et al., R. Soc. Open Sci. 11, 240262 (2024) [3] R Metzler et al., Phys. Chem. Chem. Phys. 16, 24128 (2014)

SOE 12.2 Wed 17:30 GÖR/0226

The Statistical Physics of Political Voting in German Parliament — •Moritz Marpe[1] and Carolin Dylla[2] — [1]Technical University Berlin — [2]Freie Universität Berlin

We propose a singular value decomposition (SVD) of the German parliament voting records from 2021-2024 to answer the question of how polarised was the legislature during the Ampel administration? Arguably, political polarisation is expressed most prominently between elected representatives who can be stylised in a system of their behavioural voting patterns. We built on the work by Sirovich (2003) and Rees & Lee (2025) who analyse the partisan divide and political voting patterns in the US institutions using frameworks borrowed from statistical physics to investigate the degree of polarisation. Likewise we use the median voter theorem to identify *pivotal voters* tipping collective outcomes along mulidimensional political issues. We propose a SVD to identify the most common voting coalitions following Sirovich (2003) for the last full term of the German Bundestag. Our contribution transfers insights from the bipartisan US-system to a multiparty system in general and the German Bundestag in particular filling a vital gap in the quantitative research on political polarisation.

SOE 12.3 Wed 17:45 GÖR/0226

Analyzing political spaces to understand political realignment: The case of Switzerland — •Eckehard Olbrich[1] and Peter Achermann[2] — [1]Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany — [2]University Zürich, Zürich, Switzerland

The rise of right-wing populist parties and the preceding emergence of new left and ecological parties beginning at the end of the 70s in the last century if often as the emergence of a new conflict line (”cleavage”) [1] related to the transition from industrial societies to post-industrial societies. A fully developed political cleavage corresponds to an alignment of divisions in three layers: 1) the socio-demographic structure (structural layer), 2) the prevalent attitudes, narratives and ideologies (ideological layer) and 3) the political parties and social movements. We will test the theory of new cleavage for the case of Switzerland by analyzing political spaces derived from geographically resolved data on public votes and elections. We would expect the appearance of a new cleavage to be reflected as a new dimension in the political space, thus roughly speaking increasing the dimensionality of the political space (de-alignment) while a subsequent decline of the dimensionality could represent a re-alignment in the sense that the older cleavage gets replaced. While we observe that re-alignment as a decrease of dimensionality in the data, the picture for the de-alignment appears more complicated.

[1] S. Bornschier et al. Cleavage Formation in the 21st Century: How Social Identities Shape Voting Behavior in Contexts of Electoral Realignment. Cambridge University Press, 2024.

SOE 13: Members' Assembly

Time: Wednesday 18:00–19:30 Location: GÖR/0226

All members of the Physics of Socio-economic Systems Division are invited to participate.

SOE 14: Focus Session: Physics of AI I (joint session SOE/DY)

The focus session is organized by Claudius Gros (Goethe-Universität Franfurt), Moritz Helias (Forschungszentrum Jülich), Peter Sollich (Georg-August-Universität Göttingen)

This focus session brings together experts in the field of physics-inspired theory of machine learning and artificial intelligence, who aim to supplement the engineering-driven success of AI by a principled theory of neural information processing. Contributions will address how statistical and dynamical perspectives explain learning in modern AI systems and how these insights support interpretability as well as prediction of performance, generalization, and the required resources.

Time: Thursday 9:30–11:15 Location: GÖR/0226

Invited Talk SOE 14.1 Thu 9:30 GÖR/0226

Generative AI and diffusion models: a statistical physics approach — •Giulio Biroli — Ecole Normale Superieure, Paris, France

Generative AI represents a groundbreaking development within the broader *Machine Learning Revolution,* significantly influencing technology, science, and society. In this colloquium, I will focus on the state-of-the-art *diffusion models*, which are currently used to generate images, videos, and sounds. They are very fascinating algorithms for physicists, as they are very much connected to concepts from stochastic thermodynamics, particularly time-reversed Langevin dynamics. These diffusion models start from a simple white noise input and make it evolve through a Langevin process to generate complex outputs such as images, videos, and sounds. I will show that statistical physics provides principles and methods to characterise this generation process. Specifically, I will discuss how phenomena such as the transition from memorization to generalization and the emergence of features can be understood through the lens of symmetry breaking, phase transitions, slow dynamics, and methods used to study disordered systems.

SOE 14.2 Thu 10:00 GÖR/0226

Statistical Physics of Classifier-free Diffusion Guidance — •Enrico Ventura[1], Beatrice Achilli[1], Carlo Lucibello[1], and Luca Ambrogioni[2] — [1]Bocconi University, Milan, Italy — [2]Radboud University, Nijmegen, The Netherlands

Classifier-free Guidance (CFG) is a simple yet effective technique that helps diffusion models better follow a user's prompt. By combining standard unconditional diffusion with diffusion conditioned on a specific class of the data, it steers generation toward samples (e.g. images, videos or text) that more clearly reflect the intended content. We propose a description of the sampling dynamics of a diffusion model under CFG based on the statistical mechanics of disordered systems. Specifically, we study the time-dependent transformation of the diffusion potential providing a quantitative prediction of the way a complex target distribution is deformed to improve data generation. Moreover, we leverage our results to propose alternative theory-based guidance schedules that enhance such beneficial effects.

SOE 14.3 Thu 10:15 GÖR/0226

Fundamental operating regimes, hyper-parameter fine-tuning and glassiness: towards an interpretable replica-theory for trained restricted Boltzmann machines — •Alberto Fachechi[1], Elena Agliari[1], Miriam Aquaro[1], Anthony Coolen[2], and Menno Mulder[2] — [1]Department of Mathematics, Sapienza University of Roma, P. le A. Moro 5, 00185 Roma, Italy — [2]Theoretical Biophysics, DCN Donders Institute, Faculty of Science, Radboud University, 6525 AJ Nijmegen, The Netherlands

Since the seminal work by Amit, Gutfreund and Sompolinsky, statistical mechanics of spin-glasses with structural disorder has acquired a crucial role in theoretical investigations of artificial neural networks, as it enables the representation of their generalization and information processing capabilities as phases within the space of parameters. We study the relaxation towards equilibrium of the training procedure of restricted Boltzmann machines with a binary visible layer and a Gaussian hidden layer with an unlabelled dataset consisting of noisy realizations of a single ground pattern. We develop a statistical mechanics framework to describe the network generative capabilities by exploiting replica theory. We outline the effective control parameters (e.g., the relative number of weights to be trained, the regularization parameter), whose tuning can yield qualitatively different operative regimes. We also provide analytical and numerical evidence for the existence of a sub-region in the space of the hyperparameters where replica-symmetry breaking occurs.

SOE 14.4 Thu 10:30 GÖR/0226

Mirror, Mirror of the Flow: How Does Regularization Shape Implicit Bias? — •Tom Jacobs, Chao Zhou, and Rebekka Burkholz — CISPA Helmholtz Center, Saarbrucken, Germany

Implicit bias plays an important role in explaining how overparameterized models generalize well. Explicit regularization like weight decay is often employed in addition to prevent overfitting. While both concepts have been studied separately, in practice, they often act in tandem. Understanding their interplay is key to controlling the shape and strength of implicit bias, as it can be modified by explicit regularization. To this end, we incorporate explicit regularization into the mirror flow framework and analyze its lasting effects on the geometry of the training dynamics, covering three distinct effects: positional bias, type of bias, and range shrinking. The mirror flow framework relies on Noether style parameter symmetry preservation, the regularization controls them. Our analytical approach encompasses a broad class of problems, including sparse coding, matrix sensing, single-layer attention, and LoRA, for which we demonstrate the utility of our insights. To exploit the lasting effect of regularization and highlight the potential benefit of dynamic weight decay schedules, we propose to switch off weight decay during training, which can improve generalization, as we demonstrate in experiments.

SOE 14.5 Thu 10:45 GÖR/0226

Generalization performance of narrow one-hidden layer networks in the teacher-student setting — Rodrigo Pérez Ortiz[1], •Gibbs Nwemadji[2], Jean Barbier[3], Federica Gerace[1], Alessandro Ingrosso[4], Clarissa Lauditi[5], and Enrico Malatesta[6] — [1]Alma Mater Studiorum * Università di Bologna (Unibo), Bologna, Italy — [2]International School of Advanced Studies (SISSA), Trieste, Italy — [3]The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy — [4]Radboud University, Nijmegen, The Netherlands — [5]Harvard University, Cambridge, US — [6]Bocconi University, Milano, Italy

Generalization on simple input-output distributions is best studied in the teacher-student setting, but fully connected one-hidden-layer networks with generic activations still lack a complete theory. We develop such a framework for networks with a large but finite number of hidden neurons, using statistical-physics tools to obtain closed-form predictions for both Bayesian and ERM estimators through a few summary statistics. We also identify a specialization transition when the sample size matches the number of parameters. The resulting theory accurately predicts generalization errors for networks trained with Langevin dynamics or standard full-batch gradient descent.

SOE 14.6 Thu 11:00 GÖR/0226

Testing generalization through tiny task switching frameworks — •Daniel Henrik Nevermann and Claudius Gros — Institut für Theoretische Physik, Goethe-Universität Frankfurt, Deutschland

With an ever-growing interest in advancing the performance and efficiency of large language models (LLMs), and therein particularly the transformer architecture, the need for tiny testing frameworks is pressing, as many researchers cannot afford to train models on large GPU clusters. We here propose a tiny testing framework, extending the recently published IARC task switching framework, that despite being trivial to implement offers suitable complexity to be non-trivial to learn for small scale transformer models with a few million parameters or less. Beyond model benchmarking, the framework is also suitable for probing phenomena relevant to problems arising in physics of AI, where controlled, interpretable testbeds are essential. The proposed training and evaluation scheme relies on integer sequences to be predicted by the model. These integer sequences are generated by simple deterministic tasks designed to abstract typical challenges arising in natural language processing, such as short and long range correlations, or context awareness. Within the sequences, tasks are randomly switched, where a switch is indicated by a control token. An important quality of LLMs is the ability to generalize at inference time. We here extend the existing task switching framework with new tasks able to probe models generalization capacities in a tiny, yet meaningful manner.

SOE 15: Networks: From Topology to Dynamics III (joint session DY/SOE)

Time: Thursday 11:15–12:45 Location: ZEU/0118

SOE 15.1 Thu 11:15 ZEU/0118

Remote Tipping in Networks — •Philip Marszal[1], Malte Schröder[1], and Marc Timme[1,2] — [1]Chair of Network Dynamics, Center for Advancing Electronics Dresden (cfaed) and Institute of Theoretical Physics, TUD Dresden University of Technology, 01062 Dresden, Germany — [2]Lakeside Labs, Lakeside B04b , 9020 Klagenfurt, Austria

Tipping of a single unit in a complex networked system can trigger large-scale cascades that shift the system's macroscopic state. Typically, such cascades propagate diffusively, with each tipping event destabilizing adjacent units.

Here we report a novel form of tipping cascade in systems of coupled bistable oscillators, that results in the tipping of non-adjacent nodes. One node can trigger transitions in distant nodes while intermediate neighbors remain unaffected. Which nodes tip and which ones remain unaffected depends intricately on the local oscillator dynamics and the underlying network structure. We study the transition between locally spreading and non-local cascades and characterize the conditions necessary for the emergence of non-local cascades.

SOE 15.2 Thu 11:30 ZEU/0118

Ponderomotive Route to Tipping in Open Networks — Seungjae Lee[1], •Marisa Fischer[1], and Marc Timme[1,2,3] — [1]Chair for Network Dynamics, Institute of Theoretical Physics and Center for Advancing Electronics Dresden (cfaed), Technische Universität Dresden, 01062 Dresden, Germany — [2]Center Synergy of Systems, Technische Universität Dresden, 01062 Dresden, Germany — [3]Lakeside Labs, Lakeside B04b, 9020 Klagenfurt, Austria

External fluctuations impact the dynamics of complex networked systems, from cells and ecosystems to engineered infrastructures. Strong external forcing may cause tipping that compromises such systems' functionality. Here, we identify a generic ponderomotive route to tipping in open, periodically driven systems. Upon increasing the driving amplitude, the time-average of the oscillatory responses persistently shifts away from the original system's operating point – a system-level ponderomotive effect. We characterize the shift as the fixed-point solution of a slow dynamics resulting from a two-time-scale analysis. A bifurcation point of the shift defines the tipping point beyond which the system settles into another collective state, diverges gradually, or exhibits finite-time blow-up. The ponderomotive shift together with its bifurcation yields the novel type of *ponderomotive tipping.* It generically emerges across disparate systems from science and engineering and is independent of their diverse post-tipping dynamics.

SOE 15.3 Thu 11:45 ZEU/0118

Linear dynamics on infinite networks — •Bernd Michael Fernengel — HIFMB, Oldenburg, Germany

Linear evolutionary equations are often used to describe the time evolution of a physical system. Their solution operator can be written in an exponential form of exp(t A), with some generator A. When the generator is a finite dimensional matrix, we can interpret its time evolution as a hopping dynamics on a finite network, where the dynamics of the network can be transferred to the dynamics of the solution operator.

In order to study special types of solution operators for non-interacting systems of countable dimensions, we construct countable, infinitely large networks using the iterated Cartesian product of finite graphs, where the dynamics is known. We discuss the possibilities to infer properties like the time evolution and the stationary solution of the infinite network from finite approximations via the thermodynamic limit. This is closely related to the question, under which conditions it is possible to approximate a countable, infinite system by finite subsystems.

SOE 15.4 Thu 12:00 ZEU/0118

Localizing sparse perturbation sources in driven nonlinear networks — •Julian Luca Fleck, Jose Casadiego, and Marc Timme — Chair of Network Dynamics, Center for Advancing Electronics Dresden (cfaed) and Institute of Theoretical Physics, TUD Dresden University of Technology, 01062 Dresden, Germany

Network dynamical systems under the influence of external perturbations abound in nature and engineered systems, ranging from neural circuits to electrical power grids. The external driving can drastically change the system's operating mode and be fatal for system stability. Localizing sources of perturbations in a network is crucial to mitigate systems failure. We present a linear response approach to infer the location from a multivariate time series of a recorded subset of nodes. We employ a compressed-sensing algorithm to locate one or multiple perturbation sources utilizing the sparsity of such locations. The approach additionally yields the time series of the unmeasured nodes and the external driving. We test for random linear systems, and illustrate the applicability to electrical power grids.

SOE 15.5 Thu 12:15 ZEU/0118

Elucidating structure-function relationships in physical networks via ensnarlment — •Yu Tian[1,2,3,4], Chinmayi Subramanya[1,3,4], and Carl Modes[1,3,4] — [1]Center for Systems Biology Dresden, Dresden, Germany — [2]Max Planck Institute for the Physics of Complex Systems — [3]Max Planck Institute of Molecular Cell Biology and Genetics — [4]Dresden University of Technology, Dresden, Germany

Understanding physical networks – whose structure is constrained by the physical properties of their nodes and links – is a growing interdisciplinary challenge, especially in biological systems. Physical constraints such as volume exclusion and non-crossing conditions, along with biological functionality, can drive these networks into non-optimal spatial configurations. One prominent feature is that cycles may go through each other's interior space, which may not be unraveled without removing edges, leading to an ensnarled state. Characterizing the ensnarlment in the space, and its interplay with the functional behaviours of the network, is essential for revealing structure-function relationships in such systems. In this work, we introduce a graph-theoretic framework based on the linking operator, obtained by the Gauss linking integral applied to the cycles in the network. This approach enables a multiscale analysis of entanglement, spanning local, intermediate, and global structures. Our goal is to reveal how topological complexity shapes, and is shaped by, biological functions, providing new insights into the organizational principles of physical and biological networks.

SOE 15.6 Thu 12:30 ZEU/0118

Transient stability properties for transitions between stationary power flows — •Leo Heidweiler[1,2] and Frank Hellmann[2] — [1]TU Dresden — [2]Potsdam Institute for Climate Impact Research

The increasing incorporation of renewable energy sources into electrical power grids fundamentally changes their dynamical behaviour and introduces new challenges for system stability. While network expansion and operation are traditionally based on stationary power flow analysis, dynamical effects following line faults, such as loss of synchronization of a single generator or whole part of the network, may occur even when a stable post-fault power flow exists and operational constraints are fulfilled. Direct assessment of transient stability, however, requires time-resolved simulations that are computationally expensive and unsuitable for large-scale planning and real-time applications. This motivates the question of whether transient stability properties can be inferred from static characteristics of the network, such as power flow solutions and topology.

In this work, we develop stability indicators for the IEEE39 Bus power system and investigate their predictability using PowerDynamics.jl, a Julia Library for numerical Power Grid simulations. In particular, we make use of the complex oscillator formulation of Power Systems and machine learning. This helps us assess whether stability margins can be predicted from stationary quantities alone or whether intrinsically dynamical information is indispensable. If so, we can deduce what minimal dynamical information is sufficient for reliable prediction.

SOE 16: Tipping Points in Social and Climate Systems (accompanying session for SYTP)

Accompanying session to the Symposium in Tipping Points in Social and Climate Systems

Time: Thursday 11:30–12:45 Location: GÖR/0226

Invited Talk SOE 16.1 Thu 11:30 GÖR/0226

Tipping in Strongly Perturbed Open Networks — •Marc Timme[1,2], Georg Börner[1], Marisa Fischer[1], Julian Fleck[1], Seungjae Lee[1], Philip Marszal[1], Gwendolyn Quasebarth[1], Malte Schröder[1], and Moritz Thümler[1] — [1]Network Dynamics, TU Dresden, http://networkdynamics.info — [2]Lakeside Labs, Klagenfurt, Austria

Strong fluctuations impacting open systems may induce tipping and system-wide cascading failure, yet it remains unclear under which conditions, how, and at which point fluctuation-driven systems tip. Here we report theoretical and methodological progress about tipping and its precursors in a range of externally driven nonlinear networked systems, substantially generalizing and going beyond work on one- and two-dimensional systems [1,2]. We combine self-consistency conditions, insights from periodically driven systems in electrodynamics and tools from harmonic balance and asymptotic analysis to uncover generic routes to tipping, to predict intrinsically nonlinear response dynamics before tipping and estimate the tipping point semi-analytically. We highlight several application directions and a broad range of unsolved questions.

I acknowledge generous support by the German Science Foundation (DFG) through a Koselleck project (2025-2029, proj. # 544800752).

[1] M. Thümler et al., Nonlinear and divergent responses of fluctuation-driven systems, IFAC-PapersOnLine 55:254 (2022).

[2] G. Börner et al., Perturbation-response dynamics of coupled nonlinear systems, Chaos 34:103149 (2024).

SOE 16.2 Thu 12:00 GÖR/0226

Stability and decay of socio-political systems — •Vaishnavi Jayakumar[1], Matthew Wilson[2], and Karoline Wiesner[1] — [1]Institute for Physics and Astronomy, University of Potsdam, Germany — [2]Department of Political Science, University of South Carolina, Columbia, SC, USA

The government is a fundamental unit of modern societies. There have been many efforts to quantify different styles of governance, one of the most prominent being the V-Dem project. V-Dem provides a comprehensive set of indicators on governance quality, including the Electoral Democracy Index (EDI). Governing styles can be classified in various ways based on such indicators; this has led to many studies on the feasibility, stability, and resilience of such socio-political institutions. In our present work, we analyze the V-Dem database, spanning across 195 countries, and examine the effective lifetimes and decay dynamics of various governments and regimes. Using survival analysis methods, we model regime longevity in terms of half-life and mortality rates. We find that countries with an EDI > 0.5 approximate a fairly straightforward decay function with a well-defined half-life, whereas countries with an EDI < 0.5 display irregular lifetimes, with a trajectory that evades a simple steady-state description. This heterogeneity can be understood by accounting for the underlying drivers of both regime endurance and collapse. We further investigate how economic and institutional factors shape regime lifetimes and contribute to the observed variability. Our study thus sheds new light on the key ingredients that underpin regime stability and mortality.

SOE 16.3 Thu 12:15 GÖR/0226

Generating Representative Social Networks for modeling social tipping points — •Kamiel Gülpen and Vítor Vasconcelos — University of Amsterdam, Amsterdam, The Netherlands

Addressing some of today's most pressing challenges, from climate change to public health crises, requires triggering collective behavioral shifts through social tipping points (STPs). These phenomena have been extensively modeled using synthetic network topologies, which provide valuable theoretical insights but often incompletely represent the mixing patterns that influence tipping dynamics in real populations. Understanding when STPs occur thus requires real-world network data. While such data remains scarce, government agencies possess rich information on household, family, neighborhood, and work/school connections, but often in aggregated form due to privacy constraints. This aggregated data reveals group-level mixing patterns but lacks the individual network topology necessary for modeling diffusion processes. To bridge this gap, we present the Aggregated Social Network Unfolding (ASNU) framework, which generates representative multiplex social networks from aggregated demographic data. Applied to Amsterdam's population, ASNU reconstructs networks across social layers while preserving key structural properties. We also introduce the Social Relational Attachment (SRA) model for generating realistic social networks when aggregated edge data is unavailable. Unlike previous models relying solely on homophily, SRA incorporates both homophilic and heterophilic bonding through tunable demographic distance parameters.

SOE 16.4 Thu 12:30 GÖR/0226

Jacobian Reconstruction from Time-Series of an Opinion Dynamical Network Model and its Applicability as an Early Warning Signal for Tipping Points — •Tim Mauch — Helmholtz Institute for Functional Marine Biodiversity (HIFMB), Im Technologiepark 5, 26129 Oldenburg, Germany — Carl-von-Ossietzky University, Institute for Chemistry and Biology of the Marine Environment, Carl-von-Ossietzky Str. 9-11, 26129 Oldenburg, Germany

In social dynamical systems the early identification of critical transitions is a significant challenge. To address this, we formulate a new opinion model to enhance the understanding of tipping mechanisms in opinion dynamics and adopt a method for reconstructing the Jacobian matrix of the model from time-series data, testing its applicability for detecting critical transitions.

Inspired by meta community models from ecology, we study opinion formation using a network-based model in which nodes represent communities of interacting agents holding one of two competing opinions, and links represent avenues of migration. We analytically derive conditions for diffusion-driven pattern formation and identify a mechanism facilitating opinion diversity, where the minority opinion can reach local majority, thus creating regions of differing opinion dominance.

We then generate synthetic time series of the model and reconstruct the Jacobian matrix using only the time series data and the underlying network structure. We show that the reconstructed eigenvalues correctly capture the trend of the analytical eigenvalues when changing the model parameters towards critical transitions.

SOE 17: Focus Session: Physics of AI II (joint session SOE/DY)

Time: Friday 9:30–12:45 Location: GÖR/0226

Invited Talk SOE 17.1 Fri 9:30 GÖR/0226

What can we learn from neural quantum states? — Brandon Barton[10], Juan Carrasquilla[10], Anna Dawid[9], Antoine Georges[3,6,7,8], Megan Schuyler Moss[1,2], Alev Orfi[3,4], Christopher Roth[3], Dries Sels[3,4], Anirvan Sengupta[3,5], and •Agnes Valenti[3] — [1]Perimeter Institute for Theoretical Physics, Waterloo — [2]University of Waterloo, Waterloo — [3]Flatiron Institute, New York — [4]New York University, New York — [5]Rutgers University, New Jersey — [6]Collège de France, Paris — [7]École Polytechnique, Paris — [8]Université de Genève, Genève — [9]Universiteit Leiden, The Netherlands — [10]ETH Zürich, Switzerland

Neural quantum states (NQS) provide flexible parameterizations of quantum many-body wave-functions that serve as powerful tools for the ground-state search. At the same time, NQS offer something that standard machine-learning tasks and datasets fundamentally lack: a known underlying Hamiltonian and quantum-physics tools that allow direct examination of the encoded wavefunction. This additional structure makes NQS an interesting platform for probing the behavior of classical neural networks themselves. I will first show how pruning and scaling-law phenomena change when the learning task is the quantum wavefunction itself, and link effects depend on the underlying Hamiltonian. I will then discuss generalization and double descent through the lens of quantum observables, by analyzing how NQS fail at the interpolation threshold. Finally, I will discuss how these results relate back to practical consequences for training and architecture search in the context of the ground state search for quantum many-body systems.

SOE 17.2 Fri 10:00 GÖR/0226

The NN/QFT correspondence — •Ro Jefferson — Utrecht University

Exciting progress has recently been made in the study of neural networks by applying ideas and techniques from theoretical physics. In this talk, I will discuss a precise relation between quantum field theory and deep neural networks, the NN/QFT correspondence. In particular, I will go beyond the level of analogy by explicitly constructing the QFT corresponding to a class of networks encompassing both vanilla feedforward and recurrent architectures. The resulting theory closely resembles the well-studied O(N) vector model, in which the variance of the weight initializations plays the role of the 't Hooft coupling. In this framework, the Gaussian process approximation used in machine learning corresponds to a free field theory, and finite-width effects can be computed perturbatively in the ratio of depth to width, T/N. These provide corrections to the correlation length that controls the depth to which information can propagate through the network, and thereby sets the scale at which such networks are trainable by gradient descent. If time permits, I will discuss more recent work incorporating layerwise permutation symmetry. This analysis provides a non-perturbative description of networks at initialization, and opens several interesting avenues to the study of criticality in these models.

SOE 17.3 Fri 10:15 GÖR/0226

Online Learning Dynamics and Neural Scaling Laws for a Perceptron Classification Problem — •Yoon Thelge, Marcel Kuhn, and Bernd Rosenow — Institute for Theoretical Physics, University of Leipzig, 04103 Leipzig, Germany

Understanding neural scaling laws and emergence of power law generalisations remains a central challenge in learning dynamics. A natural setting for analysing this behaviour is the online-learning dynamics of a perceptron trained in a teacher*student scenario, where in the thermodynamic limit, the generalisation error exhibits characteristic power-law decay. In realistic classification problems, the teacher is a discrete classifier, while standard gradient-based training requires the student to have continuous outputs. Thus, in practically relevant settings the student is necessarily mismatched to the discrete teacher, a regime that is less well understood. We study this regime for a perceptron with a sign-activation teacher and an error-function student. We derive coupled differential equations for the evolution of the relevant order parameters and verify them via numerical integration and SGD simulations. For fixed learning rates, the generalisation error converges to zero as a power-law with respect to the number of training examples with an exponent of -1/3. The onset of this asymptotic regime shifts with the learning rate, and the generalisation at the onset scales with exponent -1/2, motivating the use of learning-rate schedules to enhance the effective asymptotic decay.

SOE 17.4 Fri 10:30 GÖR/0226

Power-Law Correlations in Language: Criticality vs. Hierarchical Generative Structure — •Marcel Kühn[1,2], Max Staats[1,2], and Bernd Rosenow[2] — [1]ScaDS.AI Dresden/Leipzig, Germany — [2]Institute for Theoretical Physics, University of Leipzig, 04103 Leipzig, Germany

Natural language shows power-laws beyond Zipf: the mutual information between words as a function of separation — a two-point correlation — decays approximately as a power-law, a constraint for predictive language models. In autoregressive architectures like transformers, the softmax temperature of the output controls how sharply next-word probabilities concentrate, acting as a thermodynamic knob that might tune correlations. Since phase transitions are a well-known mechanism that generate such scale-free correlations, we ask whether the observed power-law mutual information requires tuning to a critical softmax temperature. Analyzing a Markov (bigram) model, we show that, in a large-system limit, power-law mutual information emerges only at a fine-tuned critical temperature, below correlations decay exponentially. Motivated by the fact that faithful language models must go beyond bigrams and that hierarchical generative processes introducing long range interactions are more representative, we analyze an autoregressive model that perfectly emulates a specific probabilistic context-free grammar. We demonstrate that simple versions of this model preserve power-law mutual information without temperature fine-tuning, and we discuss the generality of this result for variants of the model in which deviations from the grammatical rules may occur.

SOE 17.5 Fri 10:45 GÖR/0226

Dynamics of neural scaling laws in random feature regression — •Jakob Kramp[1,2], Javed Lindner[1,2], and Moritz Helias[1,2] — [1]Institute for Advanced Simulation (IAS-6), Computational and Systems Neuroscience, Jülich Research Centre, Jülich, Germany — [2]Department of Physics, RWTH Aachen University, Aachen, Germany

Training large neural networks reveals signs of universality that hold across architectures. This holds also for overparameterized networks which converge to effective descriptions in terms of Gaussian process regression. Those simplified models, already show one ingredient of universality in form of neural scaling laws. An important ingredient are power-law distributed principal component spectra of the training data.

Past work has therefore studied the dynamics of deterministic gradient flow in linear regression with and without consideration of power-law distributed spectra. Previously, dynamics of gradient flow with power law data in a type of linear random feature model were able to mimic effects of feature learning. Our work differs from the former by presenting an approach that holds for Bayesian inference on Gaussian processes obtained by stochastic Langevin training as well as for deterministic gradient flow with or without regularization by weight decay. We obtain interpretability from an effective mean-field theory that requires fewer order parameters than previous works.

15 min. break

Invited Talk SOE 17.6 Fri 11:15 GÖR/0226

Creativity in generative AI — •matthieu wyart — JHU & EPFL

Is AI creative? Generative AI such as chatGPT or diffusion models can create new texts or images from a finite training set of examples. I will argue that AI can achieve this magical by learning how compose observed low-level elements into a new whole. I will discuss the type of correlations the model can exploit to do so, how many data are needed for that, and how it relates to a hierarchical construction of latent variables. The analysis is based on the introduction of synthetic languages, and comparison with experiments performed on modern AI architectures trained on real text and images.

SOE 17.7 Fri 11:45 GÖR/0226

Understanding Generative Models via Interactions — •Claudia Merger[1,2,3], Alexandre Rene[2,4], Kirsten Fischer[2,3], Peter Bouss[2,3], Sandra Nestler[2,3], David Dahmen[2], Carsten

Honerkamp[3], Moritz Helias[2,3], and Sebastian Goldt[1] — [1]SISSA, Trieste, Italy — [2]Jülich Research Centre, Jülich, Germany — [3]RWTH Aachen University, Aachen, Germany — [4]University of Ottawa, Ottawa, Canada

Generative models have become remarkably powerful at reproducing complex data distributions. They can infer the characteristic statistics of a system from comparatively small datasets and even generate new, realistic samples. Yet, our understanding of what these models learn remains limited: which statistics do they capture, and how accurately? To address the first question, we translate the statistics learned by generative models into a central concept of statistical physics: interactions between degrees of freedom that describe how pairs, triplets, and higher-order groups coact to produce the observed statistics of a system. Using invertible neural networks, we extract these interactions directly from trained models, providing a microscopic description of their learned data structure. To assess how accurately these interactions are learned, we use an analytic theory of diffusion models that predicts the precision with which pairwise interactions can be inferred from finite datasets, quantifying how generalization depends on sample size, data hierarchy, and regularization. Together, these results provide a framework grounded in statistical physics to interpret and predict the behavior of modern generative models.

SOE 17.8 Fri 12:00 GÖR/0226

From Kernels to Features: A Multi-Scale Adaptive Theory of Feature Learning — •Javed Lindner[1,2], Noa Rubin[5], Kirsten Fischer[1,6], David Dahmen[1], Inbar Seroussi[4], Zohar Ringel[5], Michael Krämer[3], and Moritz Helias[1,2] — [1]Institute for Advanced Simulation (IAS-6), Computational and Systems Neuroscience, Jülich Research Centre, Jülich, Germany — [2]Department of Physics, RWTH Aachen University, Aachen, Germany — [3]Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Aachen, Germany — [4]Department of Applied Mathematics, School of Mathematical Sciences, Tel-Aviv University, Tel-Aviv, Israel — [5]he Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Israel — [6]RWTH Aachen University, Aachen, Germany

Feature learning in neural networks is crucial for their expressive power and inductive biases, moti- vating various theoretical approaches. Some ap- proaches describe network behavior after train- ing through a change in kernel scale from initial- ization, resulting in a generalization power com- parable to a Gaussian process. Conversely, in other approaches training results in the adapta- tion of the kernel to the data, involving directional changes to the kernel. The relationship and respective strengths of these two views have so far remained unresolved. This work presents a theo- retical framework of multi-scale adaptive feature learning bridging these two views. Using methods from statistical mechanics, we derive analytical expressions for network output statistics which are valid across scaling regimes and in the continuum between them.

SOE 17.9 Fri 12:15 GÖR/0226

Statistical physics of deep learning: Optimal learning of a multi-layer perceptron near interpolation — Jean Barbier[1], Francesco Camilli[1], Minh-Toan Nguyen[1], Mauro Pastore[1], and •Rudy Skerk[2] — [1]The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34151 Trieste, Italy — [2]International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy

We address a long-standing question in statistical physics by analysing the supervised learning of a multi-layer perceptron, beyond narrow models and kernel methods. Crucially, (i) the width scales with input dimension, making the model more prone to feature learning than ultra-wide networks and more expressive than narrow ones; and (ii) we work in the interpolation regime where trainable parameters and data are comparable, forcing task-specific adaptation. In a matched teacher-student setting we establish the fundamental limits for learning random deep-network targets and identify the sufficient statistics that an optimally trained network acquires as data increases. A rich phenomenology appears with multiple learning transitions: with enough data optimal performance arises via model "specialisation", yet practical algorithms can be trapped in theory-predicted suboptimal solutions. Specialisation occurs inhomogeneously across layers, propagating from shallow towards deep ones, but also across neurons in each layer. The Bayesian-optimal analysis thus clarifies how depth, nonlinearity and finite (proportional) width shape feature learning, with implications beyond this idealised setting.

SOE 17.10 Fri 12:30 GÖR/0226

Phase Transitions as Rank Transitions: Connecting Data Complexity and Cascades of Phase Transitions in analytically tractable Neural Network Models — •Björn Ladewig, Ibrahim Talha Ersoy, and Karoline Wiesner — Institute of Physics and Astronomy, University of Potsdam, Germany

Tuning the L2-regularization strength in neural networks can result in a cascade of (zero-temperature) phase transitions between regimes of increasing accuracy. This phenomenology was previously numerically observed and linked to a basin structure of the error landscape formed by the underlying data [1]. At the level of analytically tractable models, we (i) establish the existence of cascades of transitions for those models, (ii) give meaning to the transitions in terms of the ordered onset of "learned eigendirections" of the underlying data distribution; and (iii) link the phase transitions and corresponding accuracy regimes to saddle points of the error landscape.

[1] I. Talha Ersoy and Karoline Wiesner. Exploring l2-phase transitions on error landscapes. In ICML, Workshop on High-dimensional Learning Dynamics 2025. https://openreview.net/forum?id=AkQNtAw09u