SOE 7: Focus Session: Self-Regulating and Learning Systems: from Neural to Social Networks

Living systems have a remarkable ability to self-stabilize. How do such systems, made up of small, active units, achieve meaningful goals without global control? This focus session will explore recent advances in self-regulating networks, demonstrating how these systems transition between states, adapt to perturbations and learn to navigate new environments.

Organized by Anastasia Golovin, Johannes Zierenberg, and Viola Priesemann

Time: Wednesday 9:30–12:45 Location: H45

Invited Talk SOE 7.1 Wed 9:30 H45

When networks can think: The meaning of self-regulation in the presence of humans — •Alina Herderich — IDea_Lab, University of Graz, Austria

Feedback, global states, adaptation - given their many parallels modeling societies as self-regulating physical systems is tempting. How do the dynamics of a system change in which each of the agents has attitudes, desires, intellect? This talk explores communalities and differences between self-regulation in psychology and physics. First, I will define and illustrate the meaning of self-regulation in psychology. Second, I will explain how regulation can differ when humans regulate themselves versus others. Third, I will showcase challenges that arise when modeling groups of humans as self-regulating systems. For example, how do humans monitor the state of their group? What are the quantities that are regulated in groups of humans? And how do we differentiate between desired and undesired states especially if the targets are not morally neutral? Finally, I will close the talk with highlighting what psychology can learn from physics and vice versa in the context of self-regulating systems.

SOE 7.2 Wed 10:00 H45

Societal self-regulation induces complex infection dynamics and chaos — Joel Wagner[1,2], •Simon Bauer[1], Sebastian Contreras[1,2], Luk Fleddermann[1,2], Ulrich Parlitz[1,2], and Viola Priesemann[1,2] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]Institute for the Dynamics of Complex Systems, University of Göttingen, Göttingen, Germany

Classically, endemic infectious diseases are expected to display relatively stable, predictable infection dynamics, like recurrent seasonal waves. However, if the human population reacts to high infection numbers by mitigating the spread of the disease, this delayed behavioural feedback loop can generate infection waves itself, driven by periodic mitigation and subsequent relaxation. We show that such behavioural reactions, together with a seasonal effect of comparable impact, can cause complex and unpredictable infection dynamics, including Arnold tongues, co-existing attractors, and chaos [1]. Importantly, these arise in epidemiologically relevant parameter regions where the costs associated to infections and mitigation are jointly minimised. By comparing our model to data, we find signs that COVID-19 was mitigated in a way that favoured complex infection dynamics.Our results challenge the intuition that endemic disease dynamics necessarily implies predictability and seasonal waves, and show the emergence of complex infection dynamics when humans optimise their reaction to increasing infection numbers.

[1] Wagner, J., et al. arXiv:2305.15427

SOE 7.3 Wed 10:15 H45

Dynamical theory for adaptive biological systems — •Tuan Pham[1] and Kunihiko Kaneko[2] — [1]Institute of Physics, University of Amsterdam, Science Park 904, Amsterdam, The Netherlands — [2]Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, Copenhagen, 2100-DK, Denmark

Biological, social and neural networks are adaptive - their connections slowly change in response to the state of their constituting elements– the nodes, such as genes, individuals or neurons so as to make the collective states functionally robust under environmental stochasticity. To explain this kind of robust behavior, we develop an exact analytical theory for non-equilibrium phase transitions in multi-timescale and multi-agent dynamical systems, where there exists a correspondence between global adaptation and local learning. As an illustration of our general theory, we apply it to biological evolution, where phenotypes are shaped by gene-expression fast dynamics that are subjected to an external noise while genotypes are encoded by the configurations of a network of gene regulations. This network slowly evolves under natural selection with a mutation rate, depending on how adapted the shaped phenotypes are. Here we show how, high reciprocity of network interactions results in a trade-off between genotype and phenotype that, in turn, gives rise to a robust phase within an intermediate level of external noise. Reference: Tuan Minh Pham and Kunihiko Kaneko J. Stat. Mech. (2024) 113501.

SOE 7.4 Wed 10:30 H45

Response functions in residual networks as a measure for signal propagation — •Kirsten Fischer[1,2], David Dahmen[1], and Moritz Helias[1,3] — [1]Institute for Advanced Simulation (IAS-6), Jülich Research Centre, Jülich, Germany — [2]RWTH Aachen University, Aachen, Germany — [3]Department of Physics, Faculty 1, RWTH Aachen University, Aachen, Germany

Residual networks (ResNets) demonstrate superior trainability and performance compared to feed-forward networks, particularly at greater depths, due to the introduction of skip connections that enhance signal propagation to deeper layers. Prior studies have shown that incorporating a scaling parameter into the residual branch can further improve generalization performance. However, the underlying mechanisms behind these effects and their robustness across network hyperparameters remain unclear.

For feed-forward networks, finite-size theories have proven valuable in understanding signal propagation and optimizing hyperparameters. Extending this approach to ResNets, we develop a finite-size field theory to systematically analyze signal propagation and its dependence on the residual branch's scaling parameter. Through this framework, we derive analytical expressions for the response function, which measures the network's sensitivity to varying inputs. We obtain a formula for the optimal scaling parameter, revealing that it depends minimally on other hyperparameters, such as weight variance, thereby explaining its universality across hyperparameter configurations.

SOE 7.5 Wed 10:45 H45

Feature learning in deep neural networks close to criticality — Kirsten Fischer[1,2], •Javed Lindner[1,3,4], David Dahmen[1], Zohar Ringel[5], Michael Krämer[4], and Moritz Helias[1,3] — [1]Institute for Advanced Simulation (IAS- 6), Computational and Systems Neuroscience, Jülich Research Centre, Jülich, Germany — [2]RWTH Aachen University, Aachen, Germany — [3]Department of Physics, RWTH Aachen University, Aachen, Germany — [4]Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Aachen, Germany — [5]The Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Israel

Neural networks excel due to their ability to learn features, yet its theoretical understanding continues to be a field of ongoing research. We develop a finite-width theory for deep non-linear networks, showing that their Bayesian prior is a superposition of Gaussian processes with kernel variances inversely proportional to the network width. In the proportional limit where both network width and training samples scale as $N, P \to \infty$ with P/N fixed, we derive forward-backward equations for the maximum a posteriori kernels, demonstrating how layer representations align with targets across network layers. A field-theoretic approach links finite-width corrections of the network kernels to fluctuations of the prior, bridging classical edge-of-chaos theory with feature learning and revealing key interactions between criticality, response, and network scales.

15 min. break

Topical Talk SOE 7.6 Wed 11:15 H45

Self-organization in neural systems — •Philipp Hövel — Saarland University, Saarbrücken, Germany

Key feature of networked neural systems is the emergence of self-organized, collective dynamics giving rise to various forms of synchronization: The network is more that the sum of its parts. The nodes equiped with a neural model exhibit rich dynamical scenarious depending on the topology and type of coupling, which might also involve transmission delays due to finite signal propagation speed. In my talk, I will review a number of studies on coupled neural systems, where the considered examples include empirical, artificial, and adaptive networks. I will finish with recent results on network-induced inhibition giving rise to avalanches of neural activity interspersed by with long periods of quiescence.

SOE 7.7 Wed 11:45 H45

Critical drift in a neuro-inspired network — •Thilo Gross — Helmholtz Institute for Functional Marine Biodiversity (HIFMB) Im Technologiepark 5, 26129 Oldenburg, Germany — Alfred-Wegener Institute (AWI), Helmholtz Center for Polar and Marine Research, Bremerhaven, Germany — Carl-von-Ossietzky University, Oldenburg, Germany

It has been postulated that the brain operates in a self-organized critical state that brings multiple benefits, such as optimal sensitivity to input. Thus far, self-organized criticality has typically been depicted as a one-dimensional process, where one parameter is tuned to a critical value. However, the number of adjustable parameters in the brain is vast, and hence critical states can be expected to occupy a high-dimensional manifold inside a high-dimensional parameter space. Here, we show that adaptation rules inspired by homeostatic plasticity drive a neuro-inspired network to drift on a critical manifold, where the system is poised between inactivity and persistent activity. During the drift, global network parameters continue to change while the system remains at criticality.

SOE 7.8 Wed 12:00 H45

Transient Recurrent Dynamics Shapes Representations in Mice — •Lars Schutzeichel[1,2,3], Jan Bauer[1,4], Peter Bouss[1,2], Simon Musall[3], David Dahmen[1], and Moritz Helias[1,2] — [1]Institute for Advanced Simulation (IAS-6), Jülich Research Centre, Germany — [2]Department of Physics, Faculty 1, RWTH Aachen University, Germany — [3]Institute of Biological Information Processing (IBI-3), Jülich Research Centre, Germany — [4]The Edmond and Lily Safra Center for Brain Sciences, The Hebrew University of Jerusalem, Israel

Different stimuli evoke transient neural responses, but how is stimulus information represented and reshaped by local recurrent circuits? We address this question using Neuropixels recordings from awake mice and recurrent network models, inferring stimulus classes (e.g., visual or tactile) from activity. A two-replica mean-field theory reduces complex network dynamics to three key quantities: the mean population activity (R) and overlaps ($Q^{=}$, $Q^{\neq}$), reflecting response variability within and across stimulus classes. The theory predicts the time evolution of R, $Q^{=}$, and $Q^{\neq}$. Validated in experiments, it reveals how inhibitory balancing governs the dynamics of R, while chaotic dynamics shape overlaps, providing insights into the mechanisms underlying transient stimulus separation. The analysis of mutual information of an optimally trained population activity readout reveals that sparse coding (small R) allows the optimal information representation of multiple stimuli.

SOE 7.9 Wed 12:15 H45

Employing normalizing flows to examine neural manifold characteristics and curvatures — •Peter Bouss[1,2], Sandra Nestler[3], Kirsten Fischer[1,2], Claudia Merger[4], Alexandre René[2,5], and Moritz Helias[1,2] — [1]IAS-6, Forschungszentrum Jülich, Germany — [2]RWTH Aachen University, Germany — [3]Technion, Haifa, Israel — [4]SISSA, Trieste, Italy — [5]University of Ottawa, Canada

Despite the vast number of active neurons, neuronal population activity supposedly lies on low-dimensional manifolds (Gallego et al., 2017). To learn the statistics of neural activity, we use Normalizing Flows (NFs) (Dinh et al., 2014). These neural networks are trained to estimate the probability distribution by learning an invertible map to a latent distribution.

We adjust NF's training objectives to distinguish between relevant and noise dimensions, by using a nested dropout procedure in the latent space (Bekasov & Murray, 2020). An approximation of the network for each mixture component as a quadratic mapping enables us to calculate the Riemannian curvature tensors of the neural manifold. We focus mainly on the directions in the tangent space, in which the sectional curvature shows local extrema.

Finally, we apply the method to electrophysiological recordings of the visual cortex in macaques (Chen et al., 2022). We show that manifolds deviate significantly from being flat. Analyzing the curvature of the manifolds yields insights into the regimes where neuron groups interact in a non-linear manner.

SOE 7.10 Wed 12:30 H45

Neural self-organization of muscle-driven robots via force-mediated networks — •Claudius Gros[1] and Bulcsu Sandor[2] — [1]Institute for Theoretical Physics, Goethe University Frankfurt — [2]Department of Physics, Babes-Bolyai University, Cluj-Napoca, Romania

We present self-organizing control principles for simulated robots actuated by synthetic muscles. Muscles correspond to linear motors exerting force only when contracting, but not when expanding, with joints being actuated by pairs of antagonistic muscles. Individually, muscles are connected to a controller composed of a single neuron with a dynamical threshold that generates target positions for the respective muscle. A stable limit cycle is generated when the embodied feedback loop is closed, giving rise to regular locomotive patterns. In the absence of direct couplings between neurons, we show that the network generated by force-mediated intra- and inter-leg couplings between muscles suffice to generate stable gaits.

[1] Sándor, Bulcsú, and Claudius Gros. "Self-organized attractoring in locomoting animals and robots: an emerging field." International Conference on Artificial Neural Networks. Springer, 2024.