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

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Overview of Invited Talks and Sessions

(Lecture hall H45; Poster P4)

Invited Talks

SOE 1.1	Mon	15:00–15:30	H45	**Interplay between multiscaling and rough volatility** — •Tiziana Di Matteo
SOE 4.1	Tue	9:30–10:00	H45	**Urban scaling and conflicting goals** — •Diego Rybski
SOE 6.1	Tue	14:00–14:30	H45	**Analyzing Political Regime Stability Through the Diffusion Equation: Insights from V-Dem Data (1900-2021)** — •Karoline Wiesner
SOE 7.1	Wed	9:30–10:00	H45	**When networks can think: The meaning of self-regulation in the presence of humans** — •Alina Herderich
SOE 10.1	Thu	15:00–15:30	H45	**Emergent Behaviors in LLMs-Populated Societies** — •Giordano De Marzo, Claudio Castellano, Luciano Pietronero, David Garcia

Invited Talks of the joint SKM Dissertationspreis 2025 (SYSD)

See SYSD for the full program of the symposium.

SYSD 1.1	Mon	9:30–10:00	H2	**Nanoscale Chemical Analysis of Ferroic Materials and Phenomena** — •Kasper Aas Hunnestad
SYSD 1.2	Mon	10:00–10:30	H2	**Advanced Excitation Schemes for Semiconductor Quantum Dots** — •Yusuf Karli
SYSD 1.3	Mon	10:30–11:00	H2	**Aspects and Probes of Strongly Correlated Electrons in Two-Dimensional Semiconductors** — •Clemens Kuhlenkamp
SYSD 1.4	Mon	11:00–11:30	H2	**Mean back relaxation and mechanical fingerprints: simplifying the study of active intracellular mechanics** — •Till Münker
SYSD 1.5	Mon	11:30–12:00	H2	**Coherent Dynamics of Atomic Spins on a Surface** — •Lukas Veldman

Invited Talks of the joint Symposium Nonequilibrium Collective Behavior in Open Classical and Quantum Systems (SYQS)

See SYQS for the full program of the symposium.

SYQS 1.1	Thu	15:00–15:30	H1	**Active quantum flocks** — Reyhaneh Khasseh, Sascha Wald, Roderich Moessner, Christoph Weber, •Markus Heyl
SYQS 1.2	Thu	15:30–16:00	H1	**Robust dynamics and function in stochastic topological systems** — •Evelyn Tang
SYQS 1.3	Thu	16:00–16:30	H1	**Nonequilibrium Dynamics of Disorder-Driven Ultracold Fermi Gases** — •Artur Widera
SYQS 1.4	Thu	16:45–17:15	H1	**Topological classification of driven-dissipative nonlinear systems** — •Oded Zilberberg, Greta Villa, Kilian Seibold, Vincent Dumont, Gianluca Rastelli, Mateusz Michałek, Alexander Eichler, Javier del Pino
SYQS 1.5	Thu	17:15–17:45	H1	**Learning dynamical behaviors in physical systems** — •Vincenzo Vitelli

Sessions

SOE 1.1–1.3	Mon	15:00–16:00	H45	**Econophysics**
SOE 2.1–2.1	Mon	16:15–17:30	H45	**Award Session: Young Scientist Award for Socio- and Econophysics (YSA)**
SOE 3.1–3.10	Mon	17:30–19:30	P4	**Poster**
SOE 4.1–4.8	Tue	9:30–12:00	H45	**Urban systems, Scaling, and Social Systems**
SOE 5.1–5.3	Tue	12:15–13:00	H45	**Agent-Based Modeling**
SOE 6.1–6.3	Tue	14:00–15:00	H45	**Political Systems and Conflicts**
SOE 7.1–7.10	Wed	9:30–12:45	H45	**Focus Session: Self-Regulating and Learning Systems: from Neural to Social Networks**
SOE 8.1–8.9	Wed	15:00–17:30	H45	**Networks, From Topology to Dynamics (joint session SOE/BP/DY)**
SOE 9	Wed	18:00–19:30	H45	**Members' Assembly**
SOE 10.1–10.11	Thu	15:00–18:15	H45	**Focus Session: Large Language Models, Social Dynamics, and Assessment of Complex Systems**

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

Wednesday 18:00–19:30 H45

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

SOE 1: Econophysics

Time: Monday 15:00–16:00 Location: H45

Invited Talk SOE 1.1 Mon 15:00 H45

Interplay between multiscaling and rough volatility — •Tiziana Di Matteo — King's College London, London, UK

The multiscaling behaviour of financial time-series is one of the acknowledged stylized facts in the literature [1]. Its source in financial markets has been long debated [2,3]. In this talk I will discuss the origin of multiscaling in financial time-series, investigate how to best quantify it [4] and I will introduce a new methodology that provides a robust estimation and tests the multi- scaling property in a statistically significant way [5]. I will show results on the application of the Generalized Hurst exponent tool to different financial time-series, and I will show the powerfulness of such tool to detect changes in markets' behaviours, to differentiate markets accordingly to their degree of development, to asses risk and to provide a new tool for forecasting [6]. I will also show results to assess the interplay between price multiscaling and volatility roughness, defined as the (low) Hurst exponent of the volatility process [7] and finally I will discuss some new results on the origin of the multiscaling in rough volatility models [8]. [1] T. Di Matteo, Quantitative Finance 7(1) (2007) 21. [2] J. W Kantelhardt et al., Physica A 316 (2002) 87. [3] J. Barunik et al. Physica A 391 (2012) 4234. [4] R. J. Buonocore et al., Chaos, Solitons and Fractals 88 (2016) 38 and Phys.Rev.E, 95 (4) (2017) 042311. [5] G. Brandi, T. Di Matteo, The Eur. J. of Finance, (2021) DOI: 10.1080/1351847X.2021.1908391. [6] I. P. Antoniades et al., Physica A 565 (2021) 12556. [7] G. Brandi, T. Di Matteo, Int. Rev. Financ. Anal. 84 (2022) 102324. [8] P. Casaburi, G. Brandi, T. Di Matteo, submitted (2024).

SOE 1.2 Mon 15:30 H45

The Mechanism and Impact of Ultra Extreme Fast Events on Stock Markets — •Luca Henrichs, Anton J. Heckens, and Thomas Guhr — Universität Duisburg-Essen, Lotharstr. 1, 47048 Duisburg

Recent years have seen much discussion about the mechanism of Ultra Extreme Fast Events (UEEs), which are rapid and strong price changes. In particular, the influence of algorithmic trading or high-frequency traders (HFTs) was studied [1] [2]. HFTs are computer programs that can react faster to UEEs than humans. However, the rapid trading of HFTs would make it extremely difficult to intervene to stabilize a market. Hence, a deeper understanding of UEEs is called for.

In our study, we compare various characteristics of UEEs for the years 2007, 2008, 2014 and 2021. In comparison to the study [1], we show that various statistical properties of UEEs are robust over the years. The recovery rate after a UEE is of particular interest here and indicates that certain underlying mechanisms changed only very little. In contrast to [1], which says that human traders with large market orders generate UEEs, we concluded that liquidity plays a major role in the emergence of UEEs, independent of HFTs and human traders.

[1] Tobias Braun, Jonas A. Fiegen, Daniel C. Wagner, Sebastian M. Krause, Thomas Guhr. Impact and recovery process of mini flash crashes: An empirical study PLoS ONE 13, e0196920 (2018).

[2] Johnson N, Zhao G, Hunsader E, Qi H, Meng J, et al. Abrupt rise of new machine ecology beyond human response time. Scientific reports. 2013; 3:2627. PMID: 24022120

SOE 1.3 Mon 15:45 H45

A New Traders' Game? — Cedric Schuhmann, •Anton J. Heckens, and Thomas Guhr — Universität Duisburg-Essen, Lotharstr. 1, 47048 Duisburg

Traders on financial markets generate non–Markovian dynamics through their competition with each other. This competition can be interpreted as a game between different types of traders. We study the non–stationarity of this game and show that it has changed significantly since the global crisis of 2008.

To reveal the market mechanism, we analyze self–response functions for individual stocks as well as cross–response functions for pairs of different stocks. While the non–Markovian dynamics in the former is liquidity–driven it is only expectation–driven in the latter which might be interpreted as emergence of correlations. Averages greatly improve the statistics, we work out averaged response functions for different years. We thus considerably extend the analysis of Ref. [1,2] in which only the crisis year 2008 was studied.

[1] S. Wang, R. Schäfer and T. Guhr. Cross–Response in Correlated Financial Markets: Individual Stocks Eur. Phys. J. B 89, 105 (2016).

[2] S. Wang, R. Schäfer and T. Guhr. Average Cross–Responses in Correlated Financial Market Eur. Phys. J. B 89, 207 (2016).

SOE 2: Award Session: Young Scientist Award for Socio- and Econophysics (YSA)

Time: Monday 16:15–17:30 Location: H45

Presentation of the Award to the Awardee

Prize Talk SOE 2.1 Mon 16:30 H45

Higher-order network science — •Federico Battiston — Department of Network & Data Science, Central European University, Vienna, Austria

The complexity of many biological, social and technological systems stems from the richness of the interactions among their units. Over the past decades, a variety of complex systems has been successfully described as networks whose interacting pairs of nodes are connected by links. Yet, from human communications to ecological systems, interactions can often occur in groups of three or more nodes and cannot be described simply in terms of dyads. Until recently little attention has been devoted to the higher-order architecture of real complex systems. However, a mounting body of evidence is showing that taking the higher-order structure of these systems into account can enhance our modeling capacities and help us understand and predict their emergent dynamical behavior. Here I will present an overview of network science beyond pairwise interactions. I will discuss the higher-order organization of real-world complex systems, and characterize new emergent phenomena in dynamical processes beyond pairwise interactions, with a focus on social systems.

After the Award Session, there will be an informal get-together with beer and pretzels at the Poster Session

SOE 3: Poster

Time: Monday 17:30–19:30 Location: P4

SOE 3.1 Mon 17:30 P4

Causal Hierarchy in the Financial Market Network - Uncovered by the Helmholtz-Hodge-Kodaira Decomposition — •Tobias Wand[1,2,3], Oliver Kamps[1], and Hiroshi Iyetomi[3,4] — [1]CeNoS Münster — [2]Institut für Theoretische Physik, Universität Münster — [3]Faculty for Data Science, Rissho University, Kumagaya, Japan — [4]Canon Institute for Global Studies, Tokyo, Japan

Granger causality can uncover the cause-and-effect relationships in financial networks. However, such networks can be convoluted and difficult to interpret, but the Helmholtz-Hodge-Kodaira decomposition can split them into rotational and gradient components which reveal the hierarchy of the Granger causality flow. Using Kenneth French's business sector return time series, it is revealed that during the COVID crisis, precious metals and pharmaceutical products were causal drivers of the financial network. Moreover, the estimated Granger causality network shows a high connectivity during the crisis, which means that the research presented here can be especially useful for understanding crises in the market better by revealing the dominant drivers of crisis dynamics.

This contribution is based on the publication Wand et al., Entropy 2024, 26(10), 858 and was supported by the JSPS Summer Program.

SOE 3.2 Mon 17:30 P4

A Game-Theoretic Approach to Misinformation on Social Media — •Grace Galanthay and Eckehard Olbrich — Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany

Misinformation and disinformation are considered a significant problem with the rise of social media. While much research concentrates on the spread of information, our work focuses on the strategic actions of individual actors. Using a game-theoretic signaling framework, we study interactions where a sender communicates a noisy signal about the state of the world to a receiver, whose response determines payoffs for both actors. Existing "cheap talk" models explore strategic communication between two actors with misaligned preferences. We extend this framework to multiple senders and adapt the theoretical model to social media, where the traditional roles of sender and receiver merge. Our extension to a multi-actor signaling game in social media contexts represents a distinct approach to modeling the spread and strategic use of mis- and disinformation on digital platforms.

SOE 3.3 Mon 17:30 P4

Unraveling 20th-century political regime dynamics using the physics of diffusion — •Paula Pirker-Díaz[1], Sönke Beier[1], Matthew Wilson[2], and Karoline Wiesner[1] — [1]Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany — [2]Department of Political Science, University of South Carolina, Columbia, USA

Uncertainty remains regarding why some countries democratize while others do not, and why some remain democratic while others backslide into autocracy. Also the nature and changes of intermediate regimes is particularly unclear. By applying the Diffusion Map, a spectral dimensionality-reduction technique, on V-Dem political data (1900-2021), we identify a low-dimensional manifold describing electoral regimes. Using the diffusion equation from statistical physics, we measure the time scale on which countries change their degree of electoral quality, freedom of association, and freedom of expression depending on their position on the manifold. Democracies show subdiffusive dynamics, while collapsing autocracies exhibit super-diffusive dynamics. Intermediate regimes display distinct and more unstable diffusion behaviors, linked to a higher risk of civil conflict. This research bridges statistical physics and political science, offering a quantitative framework for understanding regime transformation and risk-of-conflict assessment. [arXiv:2411.11484]

SOE 3.4 Mon 17:30 P4

Analysis of (Mis)information Spread across Telegram Communities — Roman Ventzke[1,2], Anastasia Golovin[1,2], Sebastian Mohr[1,2], Andreas Schneider[1,2], and •Viola Priesemann[1,2] — [1]Max-Planck-Institut für Dynamik und Selbstorganisation, Göttingen — [2]Georg-August-Universität Göttingen

Statistically, do lies spread better than the truth? To effectively combat the proliferation of misinformation in online social media, it is important to understand how content spreads in social networks. We investigate the dynamics of (mis)information diffusion on the Telegram messaging platform to understand if (and how) the spread of both true information and misinformation differs.

As a basis for this study, we employ a novel large dataset of messages from Telegram group chats and channels. This dataset comprises more than 2.3 billion messages from more than 150,000 different chats and focuses on COVID-19-related content since the start of the pandemic.

Tracking information propagation, we show that information spread can be modeled by a Random Field Ising Model. Our results show that on Telegram misinformation spreads further than reliable information and is linked to "super spreaders". We also investigate whether factors like emotional engagement can drive misinformation spread.

SOE 3.5 Mon 17:30 P4

Interplay between algorithms, cognition and social interactions — •Beniamin Sereda and Janusz Hołyst — Faculty of Physics, Warsaw University of Technology, Koszykowa 75, PL-00-662 Warsaw, Poland

Modern societies are increasingly facing the issue of opinion polarisation, amplified by recommendation systems and their role in forming information cocoons. To understand how the evolution of user preferences and the topology of social networks influence opinion dynamics, the integrative agent-based model DAISY was developed. This model assumes three distinct levels of interactions: algorithmic, social, and cognitive. Algorithmic interactions are governed by recommendation algorithms, the social level reflects user preferences regarding whom to contact in the context of recommended items, and the cognitive level describes how individuals process information.The dynamics of preferences are driven by the algorithmic level, while opinion dynamics occur on the social and cognitive levels. Co-evolutional perspective on dynamics allows observation of how changes in network topology, triggered by recommendation systems, shape opinion evolution. Simulations show that increased personalisation accelerates the formation of informational cocoons, though in a non-linear and complex manner. Analysing social network evolution also revealed a deeper understanding of the irreversibility of processes within the system.

SOE 3.6 Mon 17:30 P4

Phase transition in maximally robust networks — •Thilo Gross[1,2,3] and Laura Barth[1,2,3] — [1]Helmholtz Institute for Functional Marine Biodiversity (HIFMB), Oldenburg — [2]Alfred-Wegener Institute (AWI), Helmholtz Center for Polar and Marine Research, Bremerhaven — [3]Carl-von-Ossietzky Universität Oldenburg

Here is a puzzle: You are building a network, but you know already that a certain proportion of nodes will fail, which will remove them and their links from your network. You don't know which nodes will fail, but you want your network to retain a connected component of functioning nodes that is as large as possible, after the failures have occured. Given a certain number of nodes and links, how do you connect the nodes? What kind of structure do you build?

Here we study a closely related though slightly simpler question: Instead of a fixed number of nodes and links, we consider an infinite network with a given mean degree. And, instead of allowing control over each individual link, we assume that the network is constructed as a configuration model. Hence the challenge becomes to pick the network's degree distribution such that after a certain proportion of nodes has failed the expectation value for the size of the giant component is still as large as possible.

We show this question can be solved using an analytical calculation, which reveals an infinite sequence of phase transitions between different configuration model structures.

SOE 3.7 Mon 17:30 P4

Game-theoretic model of group work contributions, neurodiverse versus neurotypical — •Lilliana Etheridge and Jens Christian Claussen — University of Birmingham, Edgbaston, UK

Evolution of cooperation and contribution to public goods have been long standing themes in game theory. Group work in the educational context, as well as teams in industry often have formalized workflows where individuals can decide to contribute different amounts. For this context, we formulate a game-theoretic model and analyze it via agent-

based simulations, both for neurotypical and neurodiverse contributors, modeled by differing decision behaviour.

SOE 3.8 Mon 17:30 P4

Weakly coupled FitzHugh-Nagumo oscillators and the influence of noise — •Max Contreras[1,2] and Philipp Hövel[2] — [1]Technische Universität Berlin, Germany — [2]Saarland University, Saarbrücken, Germany

We investigate neural oscillators modeled by FitzHugh-Nagumo systems that are weakly and diffusively coupled on a one-dimensional ring with finite coupling range. Operated in the oscillatory regime, we observe a simultaneous presence of robust collective oscillations and neuronal avalanches. The mechanism behind these avalanches is based on an inhibitory effect of interactions, which may quench the otherwise spiking of units due to an interplay with the maximal canard. The result are subthreshold oscillations close to an unstable fixed point. Furthermore, we explore the response of the networked system to noise, and find that for weak coupling, the network-mediated inhibition is weakened and that for intermediate coupling strength, noise can promote synchronized spiking.

SOE 3.9 Mon 17:30 P4

Characterizing similarities and differences in people's views based on open-ended expressions with LLMs and network science — •Ezequiel Lopez-Lopez and Stefan Herzog — Max Planck Institute for Human Development, Berlin

Citizens have diverse views on critical issues like pandemic management and climate change. Current methods to gather these views are limited: polls and surveys lack nuance, while qualitative approaches do not scale. We developed a computational framework that combines Large Language Models with network science to rapidly analyze citizens' evolving views without oversimplifying them. This novel approach extracts concepts from unstructured text and represents them in networks, offering deeper insights and faster analysis than traditional qualitative methods. We applied this framework to UK citizens' ideas on five UN Sustainable Development Goal-related policy problems. Our results demonstrate the framework's ability to capture nuanced differences across political, demographic, and cognitive variables. This approach has the potential to significantly enhance evidence-based policymaking and citizen engagement in complex societal issues.

SOE 3.10 Mon 17:30 P4

Multisensory processing in superior colliculus and primary sensory cortex — •Daniel Gerber[1], Peter Severin Graff[1,2], Björn Kampa[2], and Simon Musall[1,2,3] — [1]Institute of Biological Information Processing (IBI-3), Forschungszentrum Jülich, Jülich, Germany — [2]Department of Systems Neurophysiology, Institute for Zoology, RWTH Aachen University, Aachen, Germany — [3]Institute of Experimental Epileptology and Cognition Research, University of Bonn Medical Center, Bonn, Germany

The superior colliculus (SC) plays a crucial role in integrating multisensory stimuli and is associated with various cognitive functions, such as decision-making. It receives inputs from different sensory modalities, either directly from sensory organs or from primary sensory regions in the cortex. However, the distinctions between multisensory integration in the SC and the cortex remain unclear. To study the physiological underpinning of multisensory integration in these areas, awake mice were exposed to visual, tactile, and multisensory stimuli, while neural activity was recorded in primary visual cortex (V1), primary somatosensory cortex (S1) and the SC simultaneously using high-density Neuropixels electrodes. To investigate the influence of the cortical projection to the SC, in some trials V1 and/or S1 were optogenetically inhibited. A generalized linear model is used to analyse the spiking activity. We present that SC is modulated by cortical input but does not strongly rely on it. We also present the change in neural activity over the course of repeated stimulus.

SOE 4: Urban systems, Scaling, and Social Systems

Time: Tuesday 9:30–12:00 Location: H45

Invited Talk SOE 4.1 Tue 9:30 H45

Urban scaling and conflicting goals — •Diego Rybski — Institute of Ecological Urban and Regional Development (IOER) — Complexity Science Hub (CSH)

Urban scaling, the power-law correlations between an urban indicator and city population, represents the most famous theme of contemporary urban science. The vast majority of publications on the topic empirically quantify the scaling properties for given indicators and countries. Other work is dedicated to mathematically explaining the non-linear scaling based on few but plausible assumptions. In this contribution, two approaches to urban scaling are discussed in the context of conflicting goals. First, we compare cities in terms of emitted carbon emissions vs. heat island intensity. We derive a theoretical solution, but we find that empirical parameters do not allow for any optimal size. Instead, the fundamental allometry between area and population should represent an optimum. Thus, second, we propose a simple model that leads to an optimum in the form of the fundamental allometry. Although many cities are challenged, it makes sense that some sort of optimization takes place, which should also be reflected in observed scaling.

SOE 4.2 Tue 10:00 H45

Dynamics of Cities — Airton Deepman[1], •Renan Lucas Fagundes[2], Eugenio Megias[3], Roman Pasechnik[4], Fabiano Lemes Ribeiro[5], and Constantino Tsallis[6,7,8] — [1]USP, Sao Paulo, Brazil — [2]IOER, Dresden, Germany — [3]UGR, Granada, Spain — [4]Lund University, Lund, Sweden — [5]UFLA, Lavras, Brazil — [6]CBPF, Rio de Janeiro, Brazil — [7]SFI, Santa Fe, USA — [8]CSHV, Vienna, Austria

In recent years, the challenge has been to understand urban phenomena and their impact on the lives of people in cities in order to achieve the sustainable development goals. One of the most intriguing urban phenomena to emerge since the 1940s is fundamental allometry, which elucidates the manner in which urban areas evolve in tandem with their population size. However, most of the models in the literature investigate urban phenomena while employing the static properties of cities. In this study, we demonstrate that the combination of nonextensive statistics with fractal geometry provides a powerful tool for investigating the dynamic evolution of cities. We conducted a case study on Brazilian cities. Our findings indicate that cities evolve near the critical point of percolation, which facilitates connectivity and efficiency in space occupation. Additionally, we observed a correlation between the fractal dimension and the allometric exponent, which is associated with fundamental geometric and diffusion aspects. This research has implications for the design of infrastructure in urban areas and the promotion of economic growth. Early version of the respective manuscript: https://doi.org/10.48550/arXiv.2407.12681

SOE 4.3 Tue 10:15 H45

Scale-dependent Power Law Properties in Social Activities — •Kenta Yamada[1], Jiwei Jiang[2], Hideki Takayasu[2], and Misako Takayasu[2] — [1]Univ. of the Ryukyus, Okinawa, Japan — [2]Science Tokyo, Tokyo, Japan

This presentation explores the power-law characteristics of hashtag usage on Weibo, a Chinese social media platform. The study investigates the heavy-tailed distribution of daily hashtag frequencies and proposes a generalized random multiplicative model to understand the formation of these distributions[1].

Data containing approximately 20 million Weibo posts from July to August 2021 were analyzed. The analysis confirmed that hashtag frequency distributions follow a fat-tailed pattern, consistent with previous research[2]. A key finding was that the growth rate of hashtag usage depends on its frequency.

To model this, a generalized random multiplicative process incorporating size dependency was introduced. Simulations demonstrated that increasing granularity in dividing the hashtag frequency range improved the model's accuracy in replicating real distributions. The power-law exponents estimated through theoretical methods aligned closely with observed data.

[1] J. J. Jiang, K. Yamada, H. Takayasu, and M. Takayasu, Sci Rep 13, 1 (2023).

[2] Chen, H. H., Alexander, T. J., Oliveira, D. F., & Altmann, E. G. . Chaos, 30(6), 063112 (2020).

SOE 4.4 Tue 10:30 H45

Dynamical Power Laws in a Multiplicative Growth Model with Resets — •Alexander Jochim and Stefan Bornholdt — Institute for Theoretical Physics, University of Bremen

The observation that wealth distributions follow power laws – dating back to Pareto's 1897 work – has long intrigued physicists, offering a glimpse of universal principles in complex systems. Models based on multiplicative growth with resets are well-known for generating these heavy-tailed distributions, where the power-law exponent depends on the underlying parameters. Yet, such models often treat societal influences as static, ignoring the dynamic feedback between wealth and social behavior.

In this work, we introduce a minimal model where multiplicative growth with resets produces a wealth distribution that evolves dynamically through coupling to social mechanisms. This adaptive feedback leads to time-dependent power-law exponents, reflecting the interplay between wealth inequality and shifting societal behaviors. Our approach captures emergent phenomena in a non-equilibrium toy model for how collective social behaviors influence – and are influenced by – the statistical properties of wealth.

By framing wealth distributions as part of a coupled dynamical system, this work connects statistical physics with the study of adaptive social systems, offering fresh perspectives on the evolving patterns of inequality.

15 min. break

SOE 4.5 Tue 11:00 H45

Statistical mechanics of a voter model with an evolving number of opinion states — Jeehye Choi[1], Byungjoon Min[1,2], and •Tobias Galla[3] — [1]Department of Physics, Chungbuk National University, Cheongju, Chungbuk, Korea — [2]Department of Medicine, University of Florida, Gainesville FL, USA — [3]Institute for Cross-Disciplinary Physics and Complex Systems IFISC, Palma de Mallorca, Spain

The voter model (VM) describes population of interacting individuals. At each step a randomly chosen individual copies the state ("the opinion") of a neighbour.

Here, we introduce and study a VM in which new opinion states can be introduced spontaneously. Opinions can also go extinct via the voter dynamics. This leads to stationary states with a variable number of opinions in the population or network.

We use statistical physics methods to characterise these stationary states, drawing parallels to the evolution of "mating types" in biological populations. Mating types are forms of the sperm-egg system. Unlike for true sexes, there can be more than two mating types (some fungi have thousands). We transfer methods from number theory, previously used to characterise the evolution of mating types [1], to compute how many opinions will ultimately be present in a VM with a dynamic number of states.

[1] E. Berríos-Caro, T. Galla, G. W.A. Constable, Switching environments, synchronous sex, and the evolution of mating types, Theor. Pop. Biol. 138, 28 (2021)

SOE 4.6 Tue 11:15 H45

The noisy voter model with complete and partial aging — •Raul Toral — Institute for Cross-Disciplinary Physics and Complex Systems IFISC (CSIC-UIB), Campus UIB, 07122 Palma de Mallorca, Spain

Many agent-based models of social interaction use the Markovian assumption, namely that the transition rates from one to another state depend only on the current state of the system and not on its previous history. This, being obviously wrong in many situations, it is widely used because of its mathematical simplicity. In this work, I will consider the effect that a particular non-Markovian effect, known in the literature as "aging" or "inertia" has on the paradigmatic noisy voter model. This is a widely used model in social and economics situations to describe transitions to consensus or synchronized behavior. While the standard version of the model displays a discontinuous change of behavior from unsynchronized to consensus as a function of a parameter which depends on the free-will, or tendency to act independently on the neighbors, this transition is size-dependent and disappears in the thermodynamic limit. I will show that a genuine -second order- phase transition can appear as a consequence of aging, modeled as a reluctance to change state as a function of the length of time that has been spent in the current state. We investigate the situation where aging acts on both socially influenced and random opinion changes (complete aging), and compare it with previous results where aging acts only on pairwise interactions (partial aging).

SOE 4.7 Tue 11:30 H45

Emergence of polarization in an opinion dynamics framework with bimodal random external field — •Jan Korbel[1], Remah Dahdoul[1], Rudolf Hanel[1,2], 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 present the opinion dynamics model with an external field, where the individual opinions are coupled as in a standard Ising spin-spin interaction. Furthermore, we consider that the spins are coupled with the random field. Contrary to the common random-field Ising model, the random field is considered to be binary, either +h or -h. The interpretation of this model is that the particles represent the individuals influenced both by their neighborhood as well as external sources, e.g., election campaigns. With increasing field coupling, we observe that the transition from the ferromagnetic to paramagnetic phase becomes the first order. Furthermore, it can be shown that for a high enough field, the system becomes polarized, i.e., the external field is dominating in comparison with the spin-spin interactions. Finally, we show that for low enough temperatures, the system always gets polarized above the threshold external field, no matter whether the magnitude of the positive field is much larger or smaller than the magnitude of the negative field.

SOE 4.8 Tue 11:45 H45

Phase Transitions in Socially Balanced Systems: Why More Interactions Drive Polarization — •Markus Hofer[1,2], Jan Korbel[1,2], Rudolf Hanel[1,2], and Stefan Thurner[1,2,3] — [1]Medical University of Vienna, Center for Medical Data Science, Institute of the Science of Complex Systems, Spitalgasse 23, 1090, Vienna, Austria — [2]Complexity Science Hub Vienna, Metternichgasse 8, 1030, Vienna, Austria — [3]Santa Fe Institute, 1399 Hyde Park Rd, Santa Fe, NM 87501, USA

Survey data show massive evidence that the average number of close social connections has increased over the past two decades. At the same time opinions in societies are becoming increasingly divided. To understand if these phenomena are related, we use a multidimensional spin model [1] that has been experimentally shown [2] to be realistic both in terms of homophily and social balance. Within the model individuals interact dyadically yet realistic triad statistics as expected from social balance theory emerges naturally. We find a phase transition where at a critical connectivity of the underlying social network a rapid transition from practically no to strong polarization occurs. By understanding how increased social connectivity necessarily leads to polarization we discuss strategies to mitigate polarization in highly connected societies.

[1] T. M. Pham, J. Korbel, R. Hanel, and S. Thurner, Proceedings of the National Academy of Sciences 119, e2121103119 (2022).
[2] M. Galesic, H. Olsson, T. Pham, J. Sorger, and S. Thurner, OSF Preprints 10.31219/osf.io/3bmg7 (2023).

SOE 5: Agent-Based Modeling

Time: Tuesday 12:15–13:00 Location: H45

SOE 5.1 Tue 12:15 H45

Co-evolving networks for opinion and social dynamics in agent-based models — •Soeren Nagel[2], Quang Nuh Vu[1], and Nataša Djurdjevac Conrad[1] — [1]Zuse Institue Berlin — [2]Department of Mathematics and Computer Science, Institute of Computer Science, Freie Universität Berlin

The coevolution of public opinions and social interactions is a fundamental aspect of social systems, yet existing models often fail to include this feedback loop. While many studies explore how opinions influence social ties, The reversed influence is however often overlooked. To bridge this gap, we introduce a novel stochastic agent-based model (ABM) that integrates opinion dynamics and social mobility within a shared "social space."

The feedback loop between opinion and social dynamics generates emergent phenomena such as consensus and echo chambers, whose dynamics we analyze through a network-based order parameter. The model exhibits critical transitions for both noise intensity and relative size of opinion and social network.

Our findings demonstrate the potential of coevolutionary models to capture the transient dynamics of social clustering and opinion polarization.

Applying the model to empirical data from the General Social Survey, we investigate opinion distributions on politically charged issues, and demonstrate, that the model is capable of capturing real-world dynamics.

SOE 5.2 Tue 12:30 H45

An Agent-Based Model to Investigate Geder Bias in Peer Review — •Sophie Lake and Jens Christian Claussen — University of Birmingham, Edgbaston, UK

Fairness in the refereeing process is a challenging goal but essential to ensure the quality of the scientific publication landscape. Selfishness, various biases, friendship networks as well as time efficiency influence the behaviour of researchers when making decisions on refereeing manuscripts. A longstanding challenge is the under-representation of women in many scientific disciplines and therefore in editorial boards and referee pools. We build on a model by Thurner and Hanel (2011, EPJB 84:707) that introduced different referee strategies. Here we extend the model by gender-specific strategies, and use agent-based simulations to analyze the impact of evaluation bias, homophilic editors and friendship networks.

SOE 5.3 Tue 12:45 H45

Do weekends matter in agent-based models for epidemiology? — •Aleksandr Bryzgalov — Institut für Medizinische Epidemiologie, Biometrie und Informatik (IMEBI) Medizinische Fakultät der Martin-Luther-Universität Halle-Wittenberg, Deutschland

German Epidemic Micro-Simulation System (GEMS) is an agent-based framework that was recently developed to study and analyse the consequences of the COVID-19 pandemic.

Using GEMS we focused on a study of weekend impact on developing the infection spread throughout the population. We compared the dynamics in two cases: considering only regular days (people have constant contact rates) and considering workdays-weekends(contact rates are specific for workdays and weekends). The total number of contacts was the same in both cases. We used the transmission parameters related to the Omicron (B.1.1.529) pathogen. In our simulations, we varied the distribution of workplace sizes, but the household structure was fixed.

The results show the dependence of total attack rate of workplace size distribution: smaller workplaces in combination with workdays-weekend periodicity produce more infections than the same with only regular days. On the opposite, bigger workplaces in combination with workdays-weekend periodicity produce fewer infections than the same with only regular days.

[1] J. Ponge et al 2023 Winter Simulation Conference (WSC), San Antonio, TX, USA, 2023, pp. 1088-1099, doi: 10.1109/WSC60868.2023.10407633.

SOE 6: Political Systems and Conflicts

Time: Tuesday 14:00–15:00 Location: H45

Invited Talk SOE 6.1 Tue 14:00 H45

Analyzing Political Regime Stability Through the Diffusion Equation: Insights from V-Dem Data (1900-2021) — •Karoline Wiesner — University of Potsdam, Potsdam, Germany

Democratic stagnation and autocratic resurgence have marked the 21st century, raising questions about the stability of democracies and their implications for peace and prosperity. Utilizing the diffusion equation from statistical physics we provide firm evidence that democracy is the most stable regime type across the 20th and 21st centuries on average, surpassing the average life time of electoral autocracies. The latter also exhibit heightened susceptibility to sudden collapse. We explore these dynamics using the Diffusion Map dimensionality-reduction technique applied to V-Dem data (1900-2021). In this context, we will discuss some less explored mathematical aspects of the diffusion-map method, including its probabilistic interpretation and sensitivity to parameters and to the structure of the data. These recent results will be of interest, not least, to those wanting to apply the method to socio-economic data.

Wiesner, K., Bien, S., & Wilson, M. C. (2024). The principal components of electoral regimes: separating autocracies from pseudo-democracies. Royal Society Open Science, 11(10), 240262.

Pirker-Díaz, P., Wilson, M. C., Beier, S., & Wiesner, K. (2024). Unraveling 20th-century political regime dynamics using the physics of diffusion. arXiv preprint arXiv:2411.11484.

SOE 6.2 Tue 14:30 H45

Knowing armed conflict type hurts prediction — •Niraj Kushwaha[1], Edward D. Lee[1], and Woi Sok Oh[2] — [1]Complexity Science Hub, Austria — [2]Princeton University, USA

Moving beyond heuristic classifications of armed conflicts such as local, civil, interstate wars etc. to systematic categorization is useful but challenging. Using information-theoretic techniques we generate chains of related conflict events from the high-resolution Armed Conflict & Location Event Dataset and integrate them with other datasets spanning climate, geography, infrastructure, economics, raw demographics, and composite demographics. Using an unsupervised clustering algorithm based on multinomial mixture, we discover that three conflict archetypes exist; "major unrest," "local conflict," and "sporadic & spillover events." Major unrest predominantly occurs in densely populated areas with good infrastructure and flat, riparian geography. Local conflicts arise in mid-populated regions with diverse socio-economic and geographical features. Sporadic and spillover conflicts are small, occurring in sparsely populated areas with poor infrastructure and economic conditions. The three types stratify into a hierarchy of factors, revealing a quantitative taxonomy that highlights population, infrastructure, and economics as the most discriminative variables. Surprisingly, we find that knowing the type negatively impacts predictability of conflict intensity such as fatalities, conflict duration, and other measures of size. Hence, we develop an empirical and bottom-up approach that identifies conflict types but also cautions us about the limited utility of public data sets for conflict prediction.

SOE 6.3 Tue 14:45 H45

On the coincidence of weather extremes and geopolitical conflicts: Risk analysis in regional food markets — •Nkongho Ayuketang Arreyndip — Economic analysis of Climate Impacts and Policy Division, Euro-Mediterranean Center on Climate Change(CMCC), Via della Libertà, 12- 30175 Venice (VE), Italy.

Under increasing geopolitical tensions between important breadbaskets and climate extremes, the co-existence of weather and geopolitical extreme events can lead to devastating agricultural production losses. These losses can affect the entire food supply chain and lead to food

shortages and price increases in regional markets. This work models these events' impacts taking the Russian-Ukrainian war and the extreme heat waves of Summer 2022 as a case study. Four(4) war scenarios are considered such as the invasion phase, the peak of the war, Ukraine's resistance, sanctions against Russia, and refugee crises in Europe. Using data from the US Department of Agriculture (USDA), Statista, WITS, and Acclimate production value losses. Results show that the agricultural sectors of southern European countries such as France, Italy, and Spain were most affected by the extreme events, although the direct impact of refugees was lower compared to their northern counterparts. Strict sanctions against Russia coupled with Ukraine's resistance will benefit EU food markets, but at the same time the agricultural sectors of smaller nations and weaker economies, particularly those of Russia's allies, will be highly vulnerable. We suggest that their impact on weak economies should not be overlooked when developing and adopting conflict resolution measures.

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.

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

Time: Wednesday 15:00–17:30 Location: H45

SOE 8.1 Wed 15:00 H45

Self-organized transport in noisy dynamic networks — •Frederic Folz[1], Joshua Rainer Ganz[1], Kurt Mehlhorn[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — [2]Algorithms and Complexity Group, Max-Planck-Institut für Informatik, Saarland Informatics Campus, 66123 Saarbrücken, Germany

We present a numerical study of multicommodity transport in a noisy, nonlinear network. The nonlinearity determines the dynamics of the edge capacities, which can be amplified or suppressed depending on the local current flowing across an edge. We consider network self-organization for three different nonlinear functions: For all three we identify parameter regimes where noise leads to self-organization into more robust topologies, that are not found by the sole noiseless dynamics. Moreover, the interplay between noise and specific functional behavior of the nonlinearity gives rise to different features, such as (i) continuous or discontinuous responses to the demand strength and (ii) either single or multistable solutions. Our study shows the crucial role of the activation function on noise-assisted phenomena.

SOE 8.2 Wed 15:15 H45

Critical properties of Heider balance on multiplex networks — •Krishnadas Mohandas, Krzysztof Suchecki, and Janusz Hołyst — Faculty of Physics, Warsaw University of Technology, Koszykowa 75, PL-00-662 Warsaw, Poland

Heider's structural balance theory has proven invaluable in comprehending the dynamics of social groups characterized by both friendly and hostile relationships. Extending this understanding to multiplex networks, we investigate Heider balance dynamics in systems where agents exhibit correlated relations across multiple layers. In our model, intralayer interactions adhere to Heider dynamics, while interlayer correlations are governed by Ising interactions, using heat bath dynamics for link signs. This framework reveals a multifaceted equilibrium landscape, with distinct phases coexisting across layers. Starting from a paradise state with positive links in all layers, increasing temperature induces a discontinuous transition to disorder, similar to single-layer scenarios but with a higher critical temperature, as verified through extended mean-field analysis and agent-based simulations.

We extend this analysis to Erdös-Rényi random graphs in noisy environments. We predict a first-order transition with a critical temperature scaling as p^2 for monolayers and follow a more complex behavior for bilayers. To replicate dynamics observed in complete graphs, intralayer Heider interaction strengths must scale as p^{-2}, while interlayer interaction strengths scale as p^{-1} in random graphs. Numerical simulations confirm these analytical predictions for dense graphs.

SOE 8.3 Wed 15:30 H45

Functional Motifs in Food Webs and Networks — •Melanie Habermann[1,2,3], Ashkaan Fahimipour[4], Justin Yeakel[5,6], and Thilo Gross[1,2,3] — [1]Helmholtz Institute for Functional Marine Biodiversity (HIFMB), Oldenburg, GER — [2]Alfred-Wegener Institute (AWI), Helmholtz Center for Polar and Marine Research, Bremerhaven, GER — [3]Carl-von-Ossietzky University, Institute for Chemistry and Biology of the Marine Environment (ICBM), Oldenburg, GER — [4]Florida Atlantic University, Boca Raton, FL, USA — [5]University of California Merced, Merced, CA, USA — [6]The Santa Fe Institute, Santa Fe, NM, USA

It is interesting to ask when the presence of a small subgraph in a complex network is sufficient to impose constraints on system dynamics that are independent of the broader network structure. We refer to these subgraphs as functional motifs. A classic example can be found in ecology with the competitive exclusion motif in food webs, where two species compete for the same resource without regulation. The presence of this motif precludes any stable equilibrium for the entire system. However, examples of other motifs with similarly definitive implications for system stability are rare. But our usual notion of asymptotic stability is just one among many different concepts of stability. Another one, reactivity, captures a system's immediate response to small perturbations. In this talk, we explain why functional stability motifs are rare and show that every subgraph is a functional reactivity motif. This highlights reactivity as a promising concept for exploring a vast range of networked phenomena.

SOE 8.4 Wed 15:45 H45

Infecting Apex Predators Could Lead to Their Extinction — •Fakhteh Ghanbarnejad[1] and Hooman Saveh[2] — [1]SRH University of Applied Sciences, Leipzig, Germany — [2]Sharif University of Technology, Tehran, Iran

Food webs have been extensively studied from both ecological and mathematical aspects. However, most of the models studied in this area do not capture the effects of infectious diseases simultaneously. Recently, the idea of including an infectious disease in a food web model has been investigated. We study and simulate a small food chain consisting of only prey, predators, and apex predators governed by the generalized Lotka-Volterra equations and we implement the Susceptible-Infected-Recovered (SIR) model on only one of the species at a time in the food chain. To study the effects of an infectious disease on the food chain, we introduce a new parameter that increases predation rate by a factor of w and decreases hunting rate by a factor of $1/w$ for infected species. When the infectious disease is in our predators we observe that predators do not extinct under any set of parameters, however, an oscillation in its population size occurs under some circumstances which we do not observe in ordinary SIR or the generalized Lotka-Volterra equations alone. When an infectious disease is present in apex predators, oscillations in the population size do not happen; but if the set of parameters is in a specific range the apex predators may extinct. Furthermore, the chance of survival of the community, known as community persistence, increases for the predators and decreases for the apex predators.

15 min. break

SOE 8.5 Wed 16:15 H45

Behavioral Heterogeneity in Disease Spread: Contrasting Effects of Prevention Strategies and Social Mixing — •Fabio Sartori[1,2] and Michael Maes[1] — [1]Chair of Sociology and Computational Social Science, Karlsruhe Institute of Technology, Karlsruhe — [2]Max Planck Institute for Dynamics and Self Organisation, Göttingen, Germany

Despite mounting evidence of behavioral heterogeneity in response to disease threats, the majority of epidemiological models assume uniform behavior across populations for mathematical tractability. We analyze three distinct mechanisms of behavioral response to disease threat: susceptibility reduction (e.g., mask-wearing), active testing, and vaccination propensity. Through extensive numerical analysis, we demonstrate that the impact of behavioral heterogeneity strongly depends on the specific mechanism involved. While heterogeneous susceptibility-reducing behaviors generally decrease disease spread, heterogeneity in testing rates and vaccination propensity typically amplifies epidemic severity. Furthermore, we show that non-homogeneous mixing patterns, particularly when correlated with behavioral traits, exacerbate disease spread across all three mechanisms. These findings reveal fundamental principles about the interplay between behavioral heterogeneity and epidemic dynamics, challenging the conventional homogeneous assumption and providing important implications for public health interventions and policy design.

SOE 8.6 Wed 16:30 H45

Modelling retweet cascades using multivariate Hawkes processes on sparse networks — Alexander Kreiss[1] and •Eckehard Olbrich[2] — [1]Leipzig University, Germany — [2]Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany

We apply a model that considers vertices in a network who are able to cast events, e.g. users of the online social media platform Twitter. Furthermore, there is a directed edge from vertex A to vertex B if A takes note of the events cast by B and changes its own behavior accordingly. More precisely, the model assumes that the activity of B increases the activity of A and likewise its other neighbors. This is called peer effects. However, there might also be other information, which also influences the activity of the vertices, e.g. the time of the day for social media posts. This is called global effects. We use a Hawkes model that incorporates, both, peer and global effects. This allows for the estimation of the network, that is, the influence structure while controlling for network effects or the estimation of the global effects while controlling for peer effects. The estimation is based on

a LASSO strategy, which respects sparsity in the network. We apply this model to retweets on Twitter in order to reconstruct potential retweet cascades and identify accounts that are influential in sharing information.

SOE 8.7 Wed 16:45 H45

Influence, Incidence, Imitators and Individualists: Comparing social influence models of protective behavior in an epidemic — •Andreas Reitenbach — Karlsruhe Institute of Technology, Karlsruhe, Germany

To manage a pandemic, it is critical that citizens voluntarily engage in protective behavior (e.g. masking or vaccinating). Voluntary behavior is subject to complex dynamics of social influence, however. While various models couple social influence dynamics with disease spreading, assumptions about how individuals influence each other differ markedly. Models assuming herding implement that agents imitate their peers. On the contrary, rational agents (individualists) engage in protective behavior when their peers are not and vice versa, potentially free-riding on others' contributions to herd immunity.

Here, I study whether and why these competing behavior models translate into different disease dynamics. Following a recent call to abstract from psychological mechanisms underlying social influence, I translate the behavior theories into influence-response functions.

I find that individualists self-coordinate on a moderate level of protection and experience long-lasting but flat incidence curves. Herding, in contrast can result in rapid cycling through waves of high incidence and strong collective efforts to mitigate. Whether herders or individualists navigate an epidemic better can depend on the population's hospital capacity and disease parameters.

SOE 8.8 Wed 17:00 H45

Formalism and Physical Principles of Human Mobility and Routine — •Marlli Zambrano[1], Ashish Thampi[2], Alejandra Rincon[2], Andrzej Jarynowski[1], Steven Schulz[2], and Vitaly Belik[1] — [1]Freie Universität Berlin, Germany — [2]Machine Learning Unit, NET CHECK GmbH, Berlin, Germany

The physical principles underlying human mobility have been extensively studied in recent years, enabled by the availability of large-scale mobile phone data. While significant progress has been made in understanding general mobility patterns, capturing the dynamics of individual trajectories, specifically how mobility varies from person to person and day to day, remains challenging due to the need for highly detailed and persistent data. This study addresses this challenge by examining sequences of individual daily mobility motifs, as defined by Schneider et al., from a stochastic process perspective. The analysis uses a persistent mobile phone user panel in Berlin, with high-frequency GPS data collected over four years. Twenty motifs were identified, covering 96% of all observations. The extent of inter- and intra individual variability is explored, focusing on how motifs change within individuals over time and differ between individuals in various contexts (e.g., weekends, seasons). Additionally, sequences of motifs are modeled as a stochastic process, and properties such as transition probabilities are analyzed. These findings provide deeper insights into the variability and structure of human mobility, contributing to a better understanding of individual mobility dynamics.

SOE 8.9 Wed 17:15 H45

The world air transportation network: import risk of diseases, pandemic potentials and passenger routes — •Pascal Klamser[1,2], Adrian Zachariae[1,2], Benjamin Maier[3], Olga Baranov[4], and Dirk Brockmann[1,2] — [1]Technische Universität Dresden, Dresden, Germany — [2]Robert Koch-Institute, Berlin, Germany — [3]University of Copenhagen, Copenhagen, Denmark — [4]LMU München, München, Germany

Disease propagation between countries strongly depends on their effective distance, a measure derived from the world air transportation network. It reduces the complex spreading patterns of a pandemic to a wave-like propagation from the outbreak country, establishing a linear relationship to the arrival time of the unmitigated spread of a disease. However, in the early stages of an outbreak, what concerns decision-makers in countries is understanding the relative risk of active cases arriving in their country*essentially, the likelihood that an active case boarding an airplane at the outbreak location will reach them. While there are data-fitted models available to estimate these risks, accurate mechanistic, parameter-free models are still lacking.

We (i) introduce the "import risk" model, which defines import probabilities using the effective-distance framework, (ii) show its application to estimate the pandemic potential of emerging variants of COVID-19 and (iii) show that the effective distance shortest path tree, on which the "import risk" model is based on, is an extremely accurate representation of true passenger routes.

SOE 9: Members' Assembly

Time: Wednesday 18:00–19:30 Location: H45

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

SOE 10: Focus Session: Large Language Models, Social Dynamics, and Assessment of Complex Systems

Recent Large Language Models (LLMs) learn the statistics of human communication, and hence they present a promising way of simulating societal interactions and opinion formation. Moreover, their flexible architecture makes them versatile to also learn the statistics of other complex systems. - We will discuss how to make best use of these advancements to model social interactions and dynamics across different scales and settings, how to use them to assess sentiments, narratives and opinions, and also how one can use LLMs to also understand other complex systems. Our aim is to offer an evaluative perspective on both the potential and challenges that are intrinsic to this rapidly evolving research area.

Organized by Vincent Brockers, Johannes Zierenberg, and Viola Priesemann

Time: Thursday 15:00–18:15 Location: H45

Invited Talk SOE 10.1 Thu 15:00 H45

Emergent Behaviors in LLMs-Populated Societies — •Giordano De Marzo[1,2,3], Claudio Castellano[4,2], Luciano Pietronero[2], and David Garcia[1,3] — [1]Konstanz University — [2]CREF Enrico Fermi Research Center — [3]CSH Vienna — [4]CNR-ISC Institute for Complex Systems

Applications of Large Language Models (LLMs) increasingly involve collaborative tasks where multiple agents interact, forming "LLM societies." In this context, we explore whether large groups of LLMs exhibit emergent group behaviors similar to those in human societies. First, by simulating social network formation, we observe that LLMs spontaneously form scale-free networks. Agents connect through linear preferential attachment, mirroring the Barabasi-Albert model and real-world social networks. Second, we investigate the ability of LLMs to reach consensus on arbitrary norms without external preferences, thereby self-regulating their behavior. In human societies, consensus without institutions is limited by cognitive capacities. Similarly, we find that LLMs can reach consensus, with the opinion dynamics de-

scribed by a majority force coefficient that determines the likelihood of consensus. This majority force strengthens with higher language understanding but decreases with larger group sizes, resulting in a critical group size beyond which consensus becomes unattainable. For more advanced LLMs, this critical size grows exponentially with language capabilities, exceeding the typical size of informal human groups.

SOE 10.2 Thu 15:30 H45

A Framework for Multi-Step Discussions of LLM-Based Agents — •Vincent Brockers[1,2], David Ehrlich[2,3], and Viola Priesemann[1,2] — [1]Max Planck Institute for Dynamics and Self-Organization — [2]University of Göttingen — [3]Göttingen Campus Institute for Dynamics of Biological Networks

Recent studies have demonstrated the utility of Large Language Models (LLMs) across various settings and domains, particularly in their ability to approximate human behavior for simulating and studying societal phenomena. A critical component of this capability is their proficiency in generating realistic dialogues. We are interested in the collective dynamics that arise from their dialogues, in particular in the context of understanding collective opinion dynamics.

We developed a framework for simulating multi-step discussions among LLM-based agents, which is crucial for these studies. We conduct an in-depth analysis of the components of such simulations, highlighting the challenges and specifically investigating potential biases.

We find that these opinion dynamics are primarily influenced by model-inherent topic biases, which exhibit attractors in the opinion space. Additionally, the framing of opinion evaluation plays a crucial role in analyzing these dynamics. Our findings offer valuable insights for future research aimed at optimizing the design of LLM agent-based simulations and enhancing our modeling capabilities of complex systems, such as human networks.

SOE 10.3 Thu 15:45 H45

Collective Turing Tests on LLMs — •Azza Bouleimen[1,2], Giordano de Marzo[3], Taehee Kim[3], Silvia Giordano[2], and David Garcia[3] — [1]University of Zurich, Zurich, Switzerland — [2]SUPSI, Lugano, Switzerland — [3]University of Konstanz, Konstanz, Germany

In this project, we investigate whether social media conversations generated by independent LLMs are indistinguishable from those of humans, i.e., whether LLMs used to generate social media content can pass the Turing test. Formally, we conduct an experiment in which we prepare a series of English Reddit submissions to which we attach two conversations. One of the conversations is an authentic human conversation ,while the other is generated artificially using an LLM. We generate conversations using GPT-4o and llama 3 70B. We vary the temperatures of the models used and the length of the conversations. We recruit participants from Prolific. These subjects are asked to select the conversation they believe is generated by AI. Our preliminary results suggest that, overall, participants are fooled by LLM 40% of the time. Llama 3 70B conversations appear to fool users more often than GPT-4o ones. Through this study, we investigate to what extent and with which configurations LLM could be best used to simulate user conversations on social media. To the best of our knowledge, this is the first attempt to evaluate the performance of LLMs in mimicking a social media conversation between a group of individuals.

SOE 10.4 Thu 16:00 H45

Dialogue React: Enhancing Conversation Synthesis for Social Science Simulations — •Ruggero Marino Lazzaroni — RWTH Aachen

Recent advancements in Large Language Models (LLMs) have spurred significant progress in conversation synthesis and social dynamics modeling. However, existing approaches often fall short in generating human-like dialogues suitable for complex social science simulations and opinion formation studies. This research introduces DialogueReact, a novel framework that builds upon previous work in conversation synthesis by incorporating react prompting, dialogue acts and agentic behaviour across different scales. By leveraging LLMs' ability to learn communication statistics, DialogueReact generates qualitatively better conversations compared to previous state-of-the-art methods. Our findings demonstrate the potential of DialogueReact to improve social science research by providing an extra tool for simulating complex social interactions and understanding collective behavior in social systems.

SOE 10.5 Thu 16:15 H45

Computational modeling of LLM powered personalized recommendations — •Alessandro Bellina[1,2,4], Giordano De Marzo[1,3,4], David Garcia[3], and Vittorio Loreto[1,2,4] — [1]Centro Ricerche Enrico Fermi, Piazza del Viminale, 1, I-00184 Rome, Italy — [2]Sony Computer Science Laboratories Rome, Joint Initiative CREF-SONY, Piazza del Viminale, 1, 00184, Rome, Italy — [3]University of Konstanz, Universitaetstrasse 10, 78457 Konstanz, Germany — [4]Dipartimento di Fisica Università La Sapienza, P.le A. Moro, 2, I-00185 Rome, Italy

Large language models (LLMs) are transforming recommendation systems by tailoring content to user preferences, but they also risk reinforcing filter bubbles and driving polarization. This study investigates the dual impact of LLM-based recommendations, analyzing their inherent biases and exploring how prompt engineering can mitigate these effects. By combining synthetic simulations with real-world Twitter data, we assess how LLMs influence user behavior and the extent to which recommendations amplify or reduce polarization. Preliminary results suggest that prompt engineering enables greater control over recommendations, fostering diversity and creativity. This research provides insights into the risks and opportunities of LLM-powered systems, offering a framework for designing more inclusive and balanced recommendation algorithms.

SOE 10.6 Thu 16:30 H45

Statistical Modelling of Physics Classroom Interactions — •Niklas Stausberg, Karina Avila, Steffen Steinert, Jochen Kuhn, and Stefan Küchemann — Lehrstuhl für Didaktik der Physik, Ludwig-Maximilians-Universität München, Geschwister-Scholl-Platz 1, 80539 München

Teacher-student and student-student dialogues are one of the central means to mediate learning in classroom settings, as they foster active participation, promote cognitive engagement, scaffold conceptual understanding, and enhance metacognitive skills. However, strategies for effective classroom dialogues have primarily been studied at an organizational level, and the nuanced mechanisms through which real-time teacher-student and student-student interactions influence individual learning outcomes within the classroom remain largely unexplored.

New advances in analysis of verbal interactions now offer opportunities to perform granular analyses of classroom dialogues. Using a combination of response times and speed, voice emotion recognition, and self-regulation state detection enables clustering of patterns in students' cognitive, emotional, and self-regulatory states and map them to specific types of teacher and student responses to gain insights into the dynamics of effective classroom interactions. In this talk, we discuss how statistical modeling of classroom interactions, e.g. via percolation theory, can be used to provide additional perspectives in the understanding of social learning processes.

15 min. break

SOE 10.7 Thu 17:00 H45

Disentangling individual vs. collective contributions to polarization in political voting — Gavin Rees and •Edward Lee — Complexity Science Hub, Vienna, Austria

Politics around the world exhibit increasing polarization, most visibly demonstrated by rigid voting configurations in legislatures. This impacts their ability to seek effective compromise and pass impactful legislation. The crux of polarization is the emergence of a unidimensional ideological axis that primarily determines voting. Yet, legislative bills often negotiate multiple issues, whose effects may add up or compete for any individual vote. We develop a model inspired from statistical physics that accounts for voters with multi-dimensional preferences that can be linearly combined to generate coalitions. This allows us to capture higher-order correlations beyond those captured in direct spin-spin interaction models. As a result, the model is dramatically simpler, fits the data better, and is more interpretable than canonical maximum entropy or utility-based models from political science for large voting bodies. We study roll-call voting in US Congress, and we find coexistence of non-polarized with polarized modes. We show how increased partisan polarization is the contribution of two terms: increased party-line voting by the individual plus depletion of votes that would elicit complex, bipartisan response. Both decrease over time, but the latter falls much faster. Thus, we propose a more principled way of tracking the emergence of polarization at the level of the voter and the collective issues the many vote on.

SOE 10.8 Thu 17:15 H45

Understanding Information Spread in Social Networks through the Lense of Self-Organized Criticality: A Study on Telegram — •Roman Ventzke[1,2], Anastasia Golovin[1,2], Sebastian Bernd Mohr[1,2], Andreas Schneider[1,2], and Viola Priesemann[1,2] — [1]Max-Planck-Institut für Dynamik und Selbstorganisation, Göttingen — [2]Georg-August-Universität Göttingen

To effectively address the proliferation of misinformation in social media, one fundamentally needs to understand how information spreads in online social networks. We investigate the dynamics of information spread using a large dataset from the messenger platform Telegram, showing that information spread in the networks happens in bursty avalanches with scale-free statistics that resembles critical behavior of physical systems.

We find that the critcal exponents of the system can be well described by a mean-field Random Field Ising Model (RFIM), alluding to an important role of complex contagion and peer-pressure effects in the propagation of information. By coarse-graining dynamics in the topic space we show additional evidence that the process indeed belongs to the RFIM class. We demonstrate through simulations that the spreading process on the network can be well-described by mean-field models and discuss how self-regulation of the network gives rise to criticality.

SOE 10.9 Thu 17:30 H45

Dynamics of information spread: the phase space of topics on Telegram — •Anastasia Golovin[1,2], Simon Bauer[1], Sebastian Mohr[1], and Viola Priesemann[1,2] — [1]Max Planck for Dynamics and Self-Organisation, Göttingen, Germany — [2]Institute for the Dynamics of Complex Systems, University of Göttingen, Germany

The information that is spread on digital platforms shapes public discourse and influences decision-making. In this talk, we explore the dynamics of topics discussed on Telegram, a privacy-oriented messenger that became a hub for misinformation spread during the COVID-19 pandemic. Using transformer-based topic modeling techniques, we map each Telegram channel onto a trajectory in a high-dimensional phase space of topics. Treating these trajectories as a stochastic dynamical system, we identify topic areas that act as attractors, pulling trajectories from their neighborhood, and others that emerge only transiently in response to global events. This approach bridges computational social science and dynamical systems theory, offering a novel perspective on understanding discourse dynamics in communication networks.

SOE 10.10 Thu 17:45 H45

Computational approaches to analyzing political narratives — •Armin Pournaki[1,2,3] and Tom Willaert[4] — [1]Max Planck Institute for Mathematics in the Sciences, Leipzig, Germany — [2]Laboratoire Lattice, École Normale Supérieure - PSL - CNRS, Paris, France — [3]médialab, Sciences Po, Paris, France — [4]Brussels School of Governance, Vrije Universiteit Brussel, Brussels, Belgium

Narratives are key interpretative devices by which humans make sense of political reality. As the significance of narratives for understanding current societal issues such as polarization and misinformation becomes increasingly evident, there is a growing demand for methods that support their empirical analysis. To this end, we propose a graph-based formalism and machine-guided method for extracting, representing, and analyzing selected narrative signals from digital textual corpora, based on Abstract Meaning Representation (AMR) [1]. The formalism and method introduced here specifically cater to the study of political narratives that figure in digital trace data. We demonstrate the method on corpora gathered from archived political speeches and social media posts. [1] https://arxiv.org/abs/2411.00702

SOE 10.11 Thu 18:00 H45

Optimizing pandemic mitigation in the presence of seasonality, emerging variants and vaccination — •Laura Müller[1,2], Fabio Sartori[1,3], Jonas Dehning[1,2], Maximilian F. Eggl[4], 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 — [3]Karlsruhe Institute of Technology, Karlsruhe, Germany — [4]Institute of Neuroscience, CSIC-UMH, Alicante, Spain

Mitigation efforts are often necessary to control the spread of infectious diseases during pandemics and epidemics. However, these measures come with societal and economic costs. We present a general optimization framework based on control theory to balance the trade-off between mitigation costs and infection rates, aiming to identify the optimal time-dependent mitigation strategies across a range of scenarios: constant reproduction number, seasonal changes, emerging variants, vaccination rollout, and delayed mitigation onset. Our results show that timely reactions and proactive, preventative measures are crucial in pandemic management to save both lives and costs.