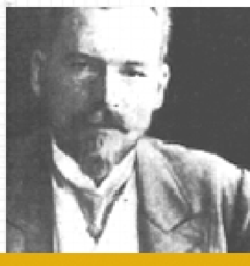
BOOK OF ABSTRACTS

Computational Neuroscience Academy 2025



38th Marian Smoluchowski Symposium on Statistical Physics

Physics of Natural and Artificial Intelligence

14-17 September, 2025, Kraków, Poland

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Conference webpage: www.smoluchowski.if.uj.edu.pl

Conference venue:

Faculty of Physics, Astronomy and Applied Computer Science;
Jagiellonian University in Kraków, Łojasiewicza 11, 30-348 Kraków

Book of Abstracts:

Wojciech Tomczyk and Bartłomiej Dybiec (editing and typesetting)

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Programme

Sunday, 14/09

11:00 – 11:20		**Registration**	
11:20 – 11:30		**Welcome Address**	
Session 1		*Neural Computing and Learning Systems*	
11:30 – 12:00	IT	*Networks of neural networks: the more is different*	Elena Agliari
12:00 – 12:30	IT	Random noise promotes slow heterogeneous synaptic dynamics important for robust working memory computation	Thiparat Chotibut
12:30 – 13:00	IT	Modeling how the brain learns to represent the world: Abstraction and Probability	Taro Toyoizumi
13:00 – 13:20	CT	Kinetic theory of nearly integrable systems	Miłosz Panfil
13:20 – 15:00		**Lunch Break**	
Session 2		*Brain Dynamics and Neurological Disorders*	
15:00 – 15:30	IT	Viral locomotion at cell surfaces: how influenza-A surfs over host defenses	Greg Huber
15:30 – 16:00	IT	Revealing spatial and temporal patterns in neuroimaging data with fractals	Jeremi K. Ochab
16:00 – 16:30	IT	Dynamics of neural motifs realized with a minimal memristive neuro-synaptic unit	Marcelo J. Rozenberg
16:30 – 16:50	CT	Measurement of the entropy production rate in a macroscopic replica of the Brownian ratchet	Antoine Naert
16:50 – 17:10	CT	Non-orthogonal eigenvectors, fluctuation-dissipation relations and entropy production	Wojciech Tarnowski
17:10 – 19:00		**Get-together meeting**	

IT Invited Talk (30 min.)   **CT** Contributed Talk (20 min.)

Monday, 15/09

Session 3		*Computational Models of Disease, Development and Evolution*	
9:00 – 9:30	IT	Stochastic modeling of telomere shortening and reconstruction	Marek Kimmel
9:30 – 10:00	IT	Site frequency spectrum and genomic mutations analysis as a possible tool in predicting the emergence of a new SARS-CoV-2 subvariants	Monika Kurpas
10:00 – 10:30	IT	Dynamics of gene expression pattern formation in growing tissues	Marcin Zagórski
10:30 – 10:50	CT	Entropy-driven adaptation response in far-from-equilibrium living systems: A theoretical model with application to radioadaptation	Krzysztof Fornalski
10:50 – 11:30		**Coffee Break**	
Session 4		*Network Science in Neurobiology and Collective Dynamics*	
11:30 – 12:00	IT	Structural balance is measurable with multidimensional attributes	Janusz Hołyst
12:00 – 12:30	IT	Hierarchy of chaotic dynamics in random modular neural networks	Łukasz Kuśmierz
12:30 – 13:00	IT	Statistical physics of drifting memory representations	Raoul-Martin Memmesheimer
13:00 – 13:20	CT	Understanding the thermodynamic limits of finite-time computation in small systems	Moupriya Das
13:20 – 13:40	CT	Spatiotemporal signatures of phase transitions in vertex models	Szymon Starzonek
13:40 – 15:00		**Lunch Break**	
Session 5		*Statistical Physics in Cellular and Neuronal Processes*	
15:00 – 15:30	IT	The hidden language of cancer genomes	Roman Jaksik
15:30 – 16:00	IT	Fluctuation-response relations for spiking nerve cells	Benjamin Lindner
16:00 – 16:20	CT	Long-term memory induces correlations and clustering of extreme events	Apurba Biswas
16:20 – 16:40	CT	The g-subdiffusion equation as a universal anomalous diffusion equation	Tadeusz Kosztołowicz

IT Invited Talk (30 min.) **CT** Contributed Talk (20 min.)

Tuesday, 16/09

Kick-off		*Introduction to the Workshops*	
9:00 – 9:30	IT	Novel methods for analyzing dynamics of functional brain networks	Mária Ercsey-Ravasz
9:30 – 10:00	IT	Revealing spatial and temporal patterns in neuroimaging data with fractals	Paweł Oświęcimka
Workshop 1			
10:15 - 12:00	IT	Brain dynamics of mammals studied through the hierarchy of complex correlation patterns defining a robust functional architecture	Mária Ercsey-Ravasz & Levente Varga
12:00 – 12:30		**Coffee Break**	
Workshop 2			
12:30 - 14:00	IT	Revealing spatial and temporal patterns in neuroimaging data with (multi)fractals	Paweł Oświęcimka, Jeremi K. Ochab & Marta Lotka
14:00 – 15:00		**Lunch Break**	
Session 6		*AI, Cognitive Neuroscience and Complex Brain Models*	
15:00 – 15:30	IT	From statistical physics to machine intelligence	Włodzisław Duch
15:30 – 16:00	IT	Learning capacity in networks of junctions with memory	Francesco Caravelli
16:00 – 18:00		**Coffee Break & Poster Session**	
18:00 –		**Gala Dinner**	

IT Invited Talk (30 min.) **CT** Contributed Talk (20 min.)

Wednesday, 17/09

Session 7		*Computational Models of Disease, Development and Evolution*	
9:00 – 9:30	IT	Price of information in games of chance	Pierpaolo Vivo
9:30 – 10:00	IT	Discontinuous phase transitions in opinion dynamics: The role of quenched disorder	Katarzyna Sznajd-Weron
10:00 – 10:30	IT	(Deep) learning to predict complex market dynamics	Silvia Bartolucci
10:30 – 10:50	CT	Tracer particles in correlated media - fluctuations and memory-induced effects	Marcin Pruszczyk
10:50 – 11:10	CT	Emergent noise control mechanism stabilizing gap gene pattern in Drosophila embryo	Maciej Majka
11:10 – 11:30		**Coffee Break**	
Session 8		*Aspects of Statistical Physics*	
11:30 - 11:50	CT	Opportunities and challenges in statistical mechanics: The fluctuation dissipation theorem and its limitations	Fernando Oliveira
11:50 – 12:10	CT	Łukasiewicz logic and Tsallis entropy connected with free projections in the free and conditionally free probability	Marek Bożejko
12:10 – 12:30	CT	Integral formulation of run-and-tumble particles in simple confinements	Derek Frydel
12:30 – 12:50	CT	Polymer chains under oscillatory force in solvents of variable quality	Bogumiła Szostak
12:50 – 13:00		**Closing Address**	
13:00 – 15:00		**Lunch Break**	

IT Invited Talk (30 min.) **CT** Contributed Talk (20 min.)

General Information

Venue

The conference will be held at the Faculty of Physics, Astronomy and Applied Computer Science of the Jagiellonian University, ul. Łojasiewicza 11 (lecture hall A1-03, 1st floor), which is about 30/40-minute ride from the city center. One can get there using the public transportation (trams number 11, 18, 52, 62 or bus number 578 and 662) to reach ”Norymberska” (or ”Ruczaj”) stop and then by taking a short walk (see page 10). Note that the direction of tram/bus (final station) should be “Czerwone Maki P+R”.

- Tram 18, 52 and 62 run through the city center.
- Tram 18 is reachable within the vicinity of Royal Castle Wawel.
- Bus 578 and 662 are reachable within the outskirts of so-called “Old Town” (*Stare Miasto).*

Registration

The Conference desk will be located in the main hall (building A, ground floor) of the Faculty of Physics, Astronomy and Applied Computer Science (see page 11). Registration will be open from 11:00 to 11:20 on Sunday, 14/09. On the other days, please consult the Symposium organizers, designated by special badges, in order to complete registration.

Invited & Contributed talks

Talks will be given in the lecture hall A1-03 (1st floor). It is advisable to use locally available computer (with Windows operating system) for the presentation (either in pdf or ppt(x) format). You can alternatively use your personal laptop, but you are kindly asked to check at least one session before your talk if all details of your file are properly projected onto the screen. Please use preferentially coffee breaks or lunch for this check and for uploading the files to the local computer. Symposium organizers will provide you with technical support.

Invited talks are scheduled for 30 minutes (including Q&A), while contributed talks are scheduled for 20 minutes (including Q&A). Chairpersons will be instructed to follow the time schedule rigorously

General Information (continued)

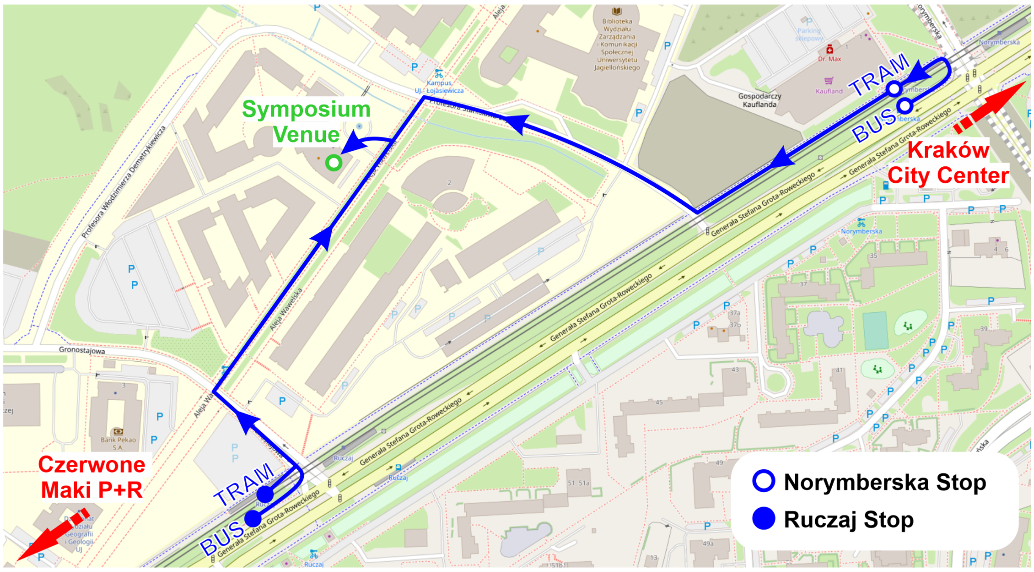
Poster session

The Poster session is scheduled for Tuesday, 16/09 at 16:00. Cork boards will be available: 120 cm x 90 cm (maximum paper size standard is A0) and pins to fix the posters. After the Poster session, posters that have not been dismounted before the lunch on Wednesday will be removed by the Organizers.

Internet access

Access via *Eduroam* and local Wi-Fi network will be available during the Symposium.

General Information (continued)



Contents

Session 1: Neural Computing and Learning Systems

Networks of neural networks: the more is different

Author: Elena Agliari[1]

[1] Sapienza Università di Roma

Corresponding Author: agliari@mat.uniroma1.it

We consider a K-layer hetero-associative neural-network and we carry out a statistical mechanical analysis. Our findings show that these networks exhibit spontaneous information processing capabilities that go far beyond those of auto-associative counterparts. In particular, they can perform frequency modulation and, when presented with a spurious state (e.g., a symmetric mixture made of K patterns), disentangle and retrieve the individual components. Furthermore, we show that this capacity is enhanced by introducing controlled perturbations—either in the training data or neuronal dynamics.

Session 1: Neural Computing and Learning Systems

Random noise promotes slow heterogeneous synaptic dynamics important for robust working memory computation

Author: Thiparat Chotibut[1]

[1] Chulalongkorn University

Corresponding Author: thiparatc@gmail.com

Recurrent neural networks (RNNs) based on model neurons that communicate via continuous signals have been widely used to study how neural circuits perform cognitive tasks. Training such networks to perform tasks that require information maintenance over a brief period (working memory tasks) remains a challenge. Inspired by the robust information maintenance observed in higher cortical areas such as the prefrontal cortex, despite substantial inherent noise, we investigated the effects of random noise on RNNs across different functions, including working memory. Our findings reveal that random noise not only speeds up training but also enhances the stability and performance of biologically plausible RNNs on working memory tasks. Importantly, this robust working memory performance induced by random noise during training is attributed to an increase in synaptic decay time constants of inhibitory units, resulting in a slower dissipative dynamics of stimulus-specific activity critical for memory maintenance. These results highlight a mechanistic role for noise in shaping network dynamics that operate near the edge of instability.

Reference

Rungratsameetaweemana, N., Kim, R., **Chotibut, T.**, Sejnowski, T. Random noise promotes slow heterogeneous synaptic dynamics important for robust working memory computation, Proceedings of the National Academy of Sciences **122**, e2316745122 (2025).

Session 1: Neural Computing and Learning Systems

Modeling how the brain learns to represent the world: ∼Abstraction and Probability∼

Author: Taro Toyoizumi[1]

[1] RIKEN Center for Brain Science

Corresponding Author: taro.toyoizumi@riken.jp

Adaptive behavior relies on activity-dependent synaptic plasticity to sculpt internal models of the world. I introduce two complementary frameworks for how the brain encodes abstraction and probability. Regarding abstract representations, we first propose a three-factor plasticity rule for nonlinear dimensionality reduction in a three-layer network inspired by the Drosophila olfactory circuit. This rule approximates the t-SNE algorithm and reproduces experimental findings from fly studies. Next, we describe a dual-pathway hippocampal model—featuring a dense, direct input path and a sparse, indirect input path—where modulation of inhibitory tone toggles recall between abstract categories and concrete exemplars. Regarding probabilistic representations, we exploit chaotic fluctuations in a recurrent network to perform Bayesian posterior sampling. Trained with biologically plausible learning on a cue-integration task, the network reliably approximates target distributions despite chaos-induced sensitivity to initial conditions. Together, these models illustrate how synaptic plasticity and neural dynamics could underlie abstract and probabilistic internal representations.

Session 1: Neural Computing and Learning Systems

Kinetic theory of nearly integrable systems

Author: Milosz Panfil[1]

[1] University of Warsaw

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Quantum integrable systems are characterised by an infinite number of conserved charges and stable quasi-particle excitations. When integrability is broken, interactions between quasi-particles are introduced, opening the way for a novel kinetic theory that incorporates both integrable and non-integrable processes. In this talk I will review recent advances in the development of such a kinetic framework, which provides new insights into a range of non-equilibrium phenomena in strongly correlated models. These include the thermalisation of homogeneous systems, the emergence of the Navier-Stokes equations, and the generalisation of the famous BBGKY hierarchy.

Session 2: Brain Dynamics and Neurological Disorders

Viral locomotion at cell surfaces: how influenza-A surfs over host defenses

Author: Greg Huber[1]

[1] University of California, San Francisco, USA

Corresponding Author: gerghuber@gmail.com

In this talk, we use various tools of statistical physics to understand how some viruses (in particular, influenza A) actively navigate through a dense, extracellular environment. We will show that an asymmetric viral surface-protein distribution not only enhances directed, persistent motion, but enables a type of sensing of their local environment. This rebuts the view that viruses are passive particles that only become active upon entry into the cell — we shall show that they locomote and sense outside of cells, using energy and actively moving up gradients in an optimal way. In addition, the physics approach can identify potential biophysical targets for novel antiviral strategies.

Session 2: Brain Dynamics and Neurological Disorders

Revealing spatial and temporal patterns in neuroimaging data with fractals

Author: Jeremi Ochab[1]
Co-authors: Marta Lotka [2]; Paweł Oświęcimka [3]

[1] Institute of Theoretical Physics, Jagiellonian University, Kraków

[2] Doctoral School of Exact and Natural Sciences, Jagiellonian University in Kraków

[3] The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

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During this lecture and workshop, we will introduce Fractal Space Curve Analysis (FSCA), a novel methodology for characterizing multidimensional data—particularly neuroimaging data—by examining their fractal properties. The core concept of FSCA is to transform multidimensional data (e.g., 2D, 3D, or 3+1D scans) into one-dimensional time series using space-filling curves (SFCs), primarily the Hilbert SFC. Detrended fluctuation analysis (DFA) is then applied to these series to quantify fractal features by extracting Hurst exponents.

To demonstrate the robustness of the method, we present FSCA tests conducted on artificially generated datasets, including two-dimensional fractional Brownian motion, Cantor sets, and Gaussian processes, as well as neuroimaging data. The results clearly show that FSCA effectively quantifies and distinguishes correlations in both stationary and dynamic two-dimensional images.

For neuroimaging data, we present results from the analysis of MRI scans, which include both healthy individuals and patients at various stages of dementia. A systematic decrease in the Hurst exponent was observed in Alzheimer's disease patients, particularly at longer scales, suggesting a reorganisation of brain structure toward greater variability as the disease progresses. Furthermore, FSCA-based features demonstrated promising performance when incorporated into machine learning classifiers for diagnostic tasks, such as distinguishing healthy controls from or AD patients and predicting mild cognitive impairment conversion to AD.

In the workshop portion practical information will be provided to enable participants to perform the analysis FSCA themselves.

Reference:

J. Grela, Z. Drogosz, J. Janarek, J.K. Ochab, I. Cifre, E. Gudowska-Nowak, M.A. Nowak, P. Oświęcimka, and D.R. Chialvo. Using space-filling curves and fractals to reveal spatial and temporal patterns in neuroimaging data. Journal of Neural Engineering 22 (2025) 016016.

Session 2: Brain Dynamics and Neurological Disorders

Dynamics of neural motifs realized with a minimal memristive neuro-synaptic unit

Author: Marcelo Rozenberg[1]

[1] CNRS, INCC Integrative Neuroscience and Cognition Center, Paris, France

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The use of electronic circuits to model neural systems goes back to C. Mead and is present in models, from leaky-integrate-and-fire to Hodking-Huxley. Simulating neural networks with analog hardware is attractive: it allows to implement neurocomputations in real time without discretization approximations, it has perfect simulation-time scaling with system size, and it provides ready-to-deploy neuromorphic circuits for applications. There are implementations in CMOS technology, however, they are complex, require sophisticated fabrication facilities and, most importantly, suffer from significant device mismatch. In a radically different approach, based on the concept of memristors, we introduce a neuro-synaptic circuit of unprecedented simplicity, with readily available cheap off-the-shelf electronic components, that can quantitatively reproduce textbook theoretical neuron and synaptic current models. Our neuron circuits can avoid the mismatch problem and are easily tunable at bio-compatible time-scales. We first introduce a voltage-gated conductance bursting neuron model that produces spike traces that bear striking similarity to experimental recordings. We then introduce synaptic current circuits and show the modularity of our method implementing neurocomputing primitives of basic network motifs, including CPGs. With this “theoretical hardware” approach we show: (i) that neuron adaptation and self-excitation can be viewed as a self-consistent dynamical problem; (ii) that a dynamical memory can be minimally implemented with a single recursive spiking neuron; (iii) that an adaptive membrane current reveals a connection between bursting and the driven harmonic oscillator, perhaps pointing to a neural correlate of the pendular limb motion. Finally we discuss the limitation of the approach to mid-size networks of mid-size and its potential application for brain-machine-interfaces, robotics and AI.

Session 2: Brain Dynamics and Neurological Disorders

Measurement of the entropy production rate in a macroscopic replica of the Brownian ratchet

Authors: A. Meynard[1]; M. Lagoin[None]; C. Crauste-Thibierge[1]; Antoine NAERT[1]

[1] ENS Lyon

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A two-states device such as the Brownian ratchet can be regarded as both a “heat engine” and an “information engine”. From this dual perspective, long time series recorded in our centimeter-scale experimental setup 1 allow for a precise investigation of all the observables of interest. These are the heat flux supplied by the athermal hot bath at $kT_{\mathrm{eff.}}$, the work produced per time unit, and, remarkably, the heat given to the surroundings at $k_{\mathrm{B}}T_{\mathrm{room}}$ (cold sink) [2]. This last heat flux is distinct from the various losses. Our experiment being at macroscopic scale, all the observables are time resolved. Processing realizations of the heat flux released to the cold sink thanks to a novel time-frequency filtering protocol, we inferred the “rate of entropy production” in the Boltzmann sense. We present a comprehensive characterization of the rate of entropy production. Our findings are compatible with a simple Poisson point process [2]. An interpretation of these results is proposed, some remaining questions are discussed. Possible generalization to other contexts is also proposed.

1 M. Lagoin, C. Crauste-Thibierge, and A. Naert, Phys. Rev. Lett., 129, 120606 (2022).
[2] A. Meynard, M. Lagoin, C. Crauste-Thibierge, and A. Naert, unpublished.

Session 2: Brain Dynamics and Neurological Disorders

Non-orthogonal eigenvectors, fluctuation-dissipation relations and entropy production

Author: Wojciech Tarnowski[1]
Co-authors: Ewa Gudowska-Nowak [1]; Maciej Nowak [1]; Yan Fyodorov [3]

[1] Institute of Theoretical Physics and Mark Kac Center for Complex Systems Research, Jagiellonian University in Kraków, Poland)

[3] King's College London, Department of Mathematics, London WC2R 2LS, United Kingdom

Corresponding Author: wojciech.tarnowski@doctoral.uj.edu.pl

Celebrated fluctuation-dissipation theorem (FDT) linking the response function to time dependent correlations of observables measured in the reference unperturbed state is one of the central results in equilibrium statistical mechanics. In this letter we discuss an extension of the standard FDT to the case when multidimensional matrix representing transition probabilities is strictly non-normal. This feature dramatically modifies the dynamics, by incorporating the effect of eigenvector nonorthogonality via the associated overlap matrix of Chalker-Mehlig type. In particular, the rate of entropy production per unit time is strongly enhanced by that matrix. We suggest, that this mechanism has an impact on the studies of collective phenomena in neural matrix models, leading, via transient behavior, to such phenomena as synchronisation and emergence of the memory. We also expect, that the described mechanism generating the entropy production is generic for wide class of phenomena, where dynamics is driven by non-normal operators. For the case of driving by a large Ginibre matrix the entropy production rate is evaluated analytically, as well as for the Rajan-Abbott model for neural networks.

Reference: Physical Review Letters 134 (8) 087102 (2025)

Session 3: Computational Models of Disease, Development and Evolution

Stochastic Modeling of Telomere Shortening and Reconstruction

Author: Marek Kimmel[1]
Co-authors: Leonard Mauvernay [2]; Marie Doumic [3]; Teresa Teixeira [4]

[1] Rice University

[2] Ecole Polytechnique

[3] INRIA Paris

[4] Institut de Biologie Physico-Chimique

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In a study involving members of Marie Doumic's group at Ecole Polytechnique (Palaiseau, France) and Maria Teresa Teixeira's group at the Institut de Biologie Physico-Chimique (Paris, France), we present a stochastic model of growth of a cell population of cultured yeast cells with gradually decaying chromosome endings, called the telomeres. Telomeres play a major role in aging and carcinogenesis in humans. The model has the form of the age-dependent Markov branching process with doubly-denumerable type space, where the type of a cell is defined as the pair of integers representing the length of telomeres at both ends of a chromosome. We derive the forward and backward Kolmogorov equations for the generating functions characterizing the process, and find that the general solutions have the form of exponential polynomials. We further derive a recursion for the coefficients of the polynomials that leads to symbolic computations. A symbolic computation computer code is used in conjunction with Monte Carlo simulations to understand the dynamics of the process, also based on previous works of Olofsson and Kimmel and members of Doumic's group. We further consider models of reconstruction of telomeres, involving cell death and the ALT mechanism, using properties of slightly supercritical branching processes, conditional on non-extinction.

Session 3: Computational Models of Disease, Development and Evolution

Site frequency spectrum and genomic mutations analysis as a possible tool in predicting the emergence of a new SARS-CoV-2 subvariants

Author: Monika Kurpas[1]
Co-authors: Daria Kostka [1]; Wiktoria Płonka [1]; Roman Jaksik [1]; Marek Kimmel [2]

[1] Silesian University of Technology, Department of Systems Biology and Engineering

[2] Rice University

Corresponding Author: monika.kurpas@polsl.pl

The rapid succession of SARS-CoV-2 variants has underscored the importance of tracing the emergence of new subvariants with evolutionary advantages. Based on almost 15 million complete viral sequences from GISAID we investigated how the individual mutations that define Variants of Concern have emerged over time. We found that rather than accumulating mutations one at a time, key changes appeared in clusters, leading to the accelerated emergence of mature variant lineages. The timing and combinatorial nature of the mutations that define each variant reveal strong but hidden selective forces at play.

This observation and analysis of the site frequency spectrum (SFS) of the viral genomes led us to the retrospective discovery of a characteristic pattern of the SFS cumulative tails, which includes a discontinuity, that can be traced down to a set of mutations that maintain identity over a certain time interval. Furthermore, the discontinuity shifts over time toward higher frequencies. Ultimately, subvariants with this cluster of mutations dominate over the parental variant. This observation leads to the potential use of prospective SFS tail analysis to identify emerging new viral substrains. In addition, we present a mechanistic model, which allows a quantitative description of the dynamics of this transient process.

Session 3: Computational Models of Disease, Development and Evolution

Dynamics of gene expression pattern formation in growing tissues

Author: Marcin Zagórski[1]

[1] Institute of Theoretical Physics and Mark Kac Center for Complex Systems Research, Jagiellonian University

Corresponding Author: marcin.zagorski@uj.edu.pl

Understanding the biophysical mechanisms that govern gene expression pattern formation is crucial for reproducible and organized organ development. Although many genetic and mechanical factors involved in pattern formation are known, we still lack a comprehensive understanding of how cellular dynamics and biomechanical feedback are orchestrated to ensure precise and reproducible patterning. In this talk, I will address this issue by presenting both a case study of ventral pattern formation in the developing spinal cord and a study of tissue development governed by mechanical factors. In the first part, I will show that after its initial establishment, the morphogen source becomes insensitive to its own signal and expands in response to tissue growth. This mechanism leads to a proportional scaling of the resulting pattern with both spinal cord size and morphogen amplitude. Such temporal decoupling of specification and growth might have implications for pattern formation in other growing organs. In the second part, I will discuss how cell elasticity, junctional tension, contractile forces, and cellular dynamics collectively affect pattern formation. Using a 2D apical vertex model, I will demonstrate how these biomechanical factors and cellular dynamics affect tissue transition from a solid-like to a fluid-like state. I will conclude by presenting results on how incorporating cell curvature can further influence pattern formation. Together, these findings identify key factors affecting patterning in growing tissues and may be broadly relevant for multiple developing tissues.

Session 3: Computational Models of Disease, Development and Evolution

Entropy-driven adaptation response in far-from-equilibrium living systems: A theoretical model with application to radioadaptation

Author: Krzysztof Fornalski[1]

[1] Wydział Fizyki, Politechnika Warszawska

Corresponding Author: krzysztof.fornalski@pw.edu.pl

Living systems are fundamentally thermodynamic structures operating far from equilibrium, characterized by continuous entropy production and driven by external energy fluxes. A key aspect of their long-term viability is their ability to adaptively regulate entropy dynamics in response to perturbations. In this contribution, we present a theoretical framework describing such entropy-driven adaptive mechanisms, with particular focus on the phenomenon of radiation adaptive response (or radioadaptation). This phenomenon is observed in biological systems exposed to low doses or low dose rates of ionizing radiation, enhances repair pathways, modulates apoptosis and cell-cycle control, and stimulates antioxidant production. We construct a general theoretical model in which this response is described as a time- and dose-dependent functions. This yields a dynamic entropy regulation mechanism, derived from first principles of stochastic thermodynamics. We analytically and numerically study the model for two distinct regimes: (1) the priming-dose scenario (Raper-Yonezawa-type effect), and (2) chronic low dose-rate irradiation, relevant for high natural background environments. The model is validated via Monte Carlo simulations and calibrated against available experimental datasets. Beyond its radiobiological relevance, our model generalizes to a broader class of far-from-equilibrium Markovian systems. We demonstrate that entropy stabilization in the steady state emerges from the interplay between external driving forces, potential barrier modulations, and system memory effects. This framework captures key features of adaptive evolution in complex systems and supports the hypothesis that adaptive regulation of entropy production seems to be a universal organizing principle in non-equilibrium statistical physics.

Session 4: Network Science in Neurobiology and Collective Dynamics

Structural balance is measurable with multidimensional attributes

Author: Janusz Hołyst[1]

Co-authors: Boleslaw Szymanski [2]; Joanna Linczuk [1]; Piotr Górski [1]

[1] Faculty of Physics, Warsaw University of Technology, Poland

[2] Social Cognitive Networks Academic Research Center, Rensselaer Polytechnic Institute, USA; Społeczna Akademia Nauk, Poland

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We study a social network where agents correspond to people, and links are relationships between agents. Each agent possesses a set of attributes. Distinguishing the signs of relationships between agents can be performed for each attribute separately or considering all attributes together. In the former case, we assume a simple edge is positive/negative when the two agents hold the same/different attribute. In the latter case, for a pair of agents i and j, a normalized distance is calculated in the multidimensional space of attributes, x_{ij}, defining the multi-edge link as follows: a link is positive when $x_{ij} \leqslant \Theta$, and it is negative otherwise where Θ is a threshold parameter. We apply our signed network construction definition to study the NetSense dataset, which contains data about relationships between university students and their opinions on important social topics. We construct simple and multidimensional triads and test for which condition Structural Balance Theory (SBT) principles can be measured in the system, i.e. "friend of my friend or enemy of my enemy is my friend" etc. Density of balanced triads and triad transition probabilities are considered . Measures obtained for the real network are compared with those for three different null models and two randomized processes. Our results show that SBT influence is not observed in the case of simple edges. Triad densities for real networks are not statistically different from densities in null models. However, in the case of multi-edges, for the range of tolerance values, multidimensional triads are significantly more balanced in the real network. This means that structural balance dynamics are measurable only when considering multidimensional attributes.

Session 4: Network Science in Neurobiology and Collective Dynamics

Hierarchy of chaotic dynamics in random modular neural networks

Author: Lukasz Kusmierz[1]
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Despite wide recognition of the modular and hierarchical organization of neural circuits in the brain, our understanding of its influence on neural dynamics and information processing remains incomplete. To address this gap, we introduced a model of randomly connected neural populations (modules) and studied its dynamics by means of the mean-field theory and simulations. Our analysis uncovered a rich phase diagram: High-dimensional chaotic activity (microscopic chaos), common in homogeneous networks, is separated from the low-dimensional chaotic activity of strongly coherent modules (macroscopic chaos) by a crossover region (multiscale chaos). In the crossover region, macroscopic and microscopic chaotic activities coexist and the dimension of activity can be interpreted as either high (according to the Lyapunov dimension) or low (according to the participation ratio dimension). Counterintuitively, chaos can be attenuated, as measured by the maximal Lyapunov exponent, by either adding quenched noise to strongly modular connectivity or by introducing modularity into random connectivity. Thus, for a given level of network activity, the network exhibits longest memory (slowest time scales) at intermediate values of modularity. We confirmed the utility of the modularity-dependent slow manifold in a simple reservoir computing task (delayed XOR), where the introduction of strong-enough modularity was required to solve the task when the encoding of inputs was noisy. Altogether, our results indicate that modular connectivity strongly affects neural dynamics and may play important roles in neural computations.

Session 4: Network Science in Neurobiology and Collective Dynamics

Statistical physics of drifting memory representations

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Change is ubiquitous in living beings. In particular, the connectome and neural representations can change. Nevertheless, behaviors and memories often persist over long times. In a standard model, associative memories are represented by assemblies of strongly interconnected neurons. For faithful storage these assemblies are assumed to consist of the same neurons over time. We propose a contrasting memory model with complete temporal remodeling of assemblies, based on experimentally observed changes of synapses and neural representations. The assemblies drift freely as noisy autonomous network activity and spontaneous synaptic turnover induce neuron exchange. The gradual exchange allows plasticity to conserve the representational structure and keep inputs, outputs, and assemblies consistent. This leads to persistent memory. We develop various statistical physics descriptions to quantitatively model the drift of assemblies in single brain regions and throughout the brain. This allows to predict the future dynamics of the neurobiologically observed initial drift of memory representations, which is usually interpreted as a sign of memory consolidation processes.

Session 4: Network Science in Neurobiology and Collective Dynamics

Understanding the thermodynamic limits of finite-time computation in small systems

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It is a general experience that computation in a computer produces heat. A part of this heat appears because of the erasure of memory, which is an essential step for irreversible logic operations in regular computational processes. The laws of thermodynamics fix a limit for the heat evolution associated with this erasure step and eventually for the computation[1, 2]. In small systems with fluctuations, the limit is set on the average value of the quantity. It is a common observation that the higher the speed of computation, the greater the amount of heat evolved. For practical situations, it is desirable to keep this heat as low as possible. However, to achieve the lower limit of the evolved heat, one needs to perform computation infinitely slowly, and that would not be a useful function. Consequently, a very important field of research has emerged very recently, which focuses upon the optimization of heat evolution for finite-time computation. This significant and practical problem has been targeted to be solved with different approaches; however, no definite solution has been found yet. We address this crucial issue to figure out what possible factors would be important to look at, which can minimize the heat evolution for a finite-time computation. We derive an analytical expression for the work done for the finite-time erasure protocol[3]. We primarily concentrate on exploring the environmental factors and shape modifications of the potential, mimicking the memory states. These are supposed to play significant roles in the understanding of the optimization of the heat involvement in the erasure process.

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[3]Giorgini et al., Phys. Rev. Research 5, 023084 (2023).

Session 4: Network Science in Neurobiology and Collective Dynamics

Spatiotemporal signatures of phase transitions in vertex models

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Vertex models provide a powerful framework for studying the mechanics and dynamics of confluent biological tissues that undergo fluid to solid-like transitions during morphogenesis. Although these transitions are often characterized by changes in macroscopic properties, the underlying microscopic dynamics, particularly their spatiotemporal fluctuations, remain weekly understood. Here, we investigate fluid-to-solid transitions in a two-dimensional vertex model by performing extensive numerical simulations. We focus on the analysis of dynamics and heterogeneities emerging in both space and time. We quantify spatiotemporal fluctuations via the four-point dynamical susceptibility and cell displacement maps. In addition, we conduct an analysis of topological defects and the nematic order parameter to characterize the structural changes during the transition. These distinct spatiotemporal signatures can be further used to compare with cellular patterns observed in biological tissues. Overall, the proposed metrics to quantify dynamics of spatial heterogeneities in confluent tissues can be applied in other disordered systems to study glass and jamming transitions.

Session 5: Statistical Physics in Cellular and Neuronal Processes

The Hidden Language of Cancer Genomes

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Whole genome sequencing is playing an increasingly central role in modern oncology, offering detailed insights that support the development of individualized treatment strategies, especially when combined with machine learning techniques. Traditional approaches that concentrate solely on identifying key driver mutations face limitations due to both the restricted sensitivity of current technologies and the still-evolving understanding of cancer biology. Notably, different alterations can trigger similar disease phenotypes, complicating straightforward interpretations. For this reason, growing emphasis is being placed on integrative methods that not only identify driver mutations but also evaluate their broader effects on genome integrity. The resulting mutational signatures — patterns that reflect underlying biological processes — are proving to be powerful tools in guiding therapeutic decisions.

In this presentation, I will discuss the main obstacles in constructing reliable genomic classifiers and share examples of effective solutions grounded in mutational pattern analysis. I will also illustrate how studying these patterns in cancer genomes can reveal fundamental mechanisms at work even in healthy cells.

Session 5: Statistical Physics in Cellular and Neuronal Processes

Fluctuation-Response Relations for spiking nerve cells

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The fluctuations and the response of stochastic systems are related by fluctuation-dissipation theorems or, equivalently, fluctuation-response relations (FRRs). Originally introduced for systems in thermodynamic equilibrium, generalizations of such relations for non-equilibrium situations have been derived and studied since the 1970's and are particularly appealing for biological systems. In my talk I report a new class of FRRs for spiking neurons that relate the pronounced fluctuations of spontaneous neural firing to their average response to sensory stimuli, i.e. to the processing of sensory information that is the raison d'etre of neural systems. Extensions of FRRs to neurons with a finite spike shape, with shot noise, or to groups of neurons that driven by common stimuli are also discussed.

Refs.:
B. Lindner 129, 198101 Phys. Rev. Lett. (2022);
F. Puttkammer and B. Lindner Biol. Cyb. 118, 7 (2024)
J. Stubenrauch & B. Lindner Phys. Rev. X 14, 041047 (2024)

Session 5: Statistical Physics in Cellular and Neuronal Processes

Long-term memory induces correlations and clustering of extreme events

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Extreme events, although rare, hold significant importance due to their huge impact in various areas of science (earthquakes, chemical reactions, population extinction, etc.). Typically, the kinetics of these events is described by Arrhenius laws, with exponentially distributed waiting times. However, this description may break down in the presence of long-term memory, i.e., for stochastic processes with correlation functions decaying as a power-law rather than exponentially, since Arrhenius times cannot be larger than (infinite) correlation times. This leads to several intriguing questions such as: (a) Do rare-events show correlations in their successive occurrences? (b) Given an extreme event, can we predict the time before next occurrence? (c) And finally, can we characterize analytically the phenomenon of rare-event clustering? Here, we analyze the kinetics to reach a rarely reached threshold for a Gaussian stationary random walker with long-term memory, as an example of the paradigmatic Kramer's escape problem. We calculate analytically the joint distribution of the last and first passage to a rarely reached threshold (relative to a specified reference point) to explore correlations and the predictability of return intervals between consecutive rare-events. Additionally, we examine the second passage distribution to an extreme event to study their clustering. We find analytically that long-term memory induces (i) non-exponential corrections in the joint distribution of last and first passage of rare-events, (ii) non-zero correlations between their occurrences, and (iii) clustering of successive rare events.

Session 5: Statistical Physics in Cellular and Neuronal Processes

The g-subdiffusion equation as a universal anomalous diffusion equation

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The g-subdiffusion equation is a subdiffusion equation containing the fractional Caputo time derivative with respect to another function g. The process described by this equation is interpreted as "ordinary" subdiffusion in which the time variable t has been replaced by an increasing function g(t). This function determines the frequency of jumps of the diffusing molecule. The g-subdiffusion equation can be derived from a modified continuous time random walk model. By defining the function g appropriately, this equation describes a smooth transition from subdiffusion to superdiffusion, to subdiffusion with changing parameters, and to slow subdiffusion (ultraslow diffusion). This equation can also describe superdiffusion (then we call it the g-superdiffusion equation), providing solutions that in the long-time limit are consistent with solutions of the fractional superdiffusion equation with the spatial fractional Riesz-Weyl type derivative. For the g-superdiffusion equation, the problem of assuming local boundary conditions at partially permeable thin membranes does not arise.

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Kick-off: Introduction to Workshops

Novel methods for analyzing dynamics of functional brain networks

Authors: Maria-Magdolna Ercsey-Ravasz[1]; Levente Varga[2]

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Our workshop will begin with a presentation by Dr. Maria Ercsey-Ravasz on recently published methods for analyzing functional network (FN) dynamics in the brain (Varga et al., Cell Systems, 15, 1–17, 2024). This approach considers time lags when constructing functional brain networks and utilizes the statistical distribution of network properties rather than analyzing a single, averaged network. By doing so, it reveals a stable functional architecture characterized by a strong 0-lag backbone and weaker, yet informative, links at various time delays. In the second part of the workshop, Dr. Levente Varga will teach participants how to use our freely available software for analyzing datasets: extracting functional networks, examining their properties, comparing different groups, and more. We will also provide examples of how this method can be employed to develop novel biomarkers in the study of various pathologies.

Kick-off: Introduction to Workshops

Revealing spatial and temporal patterns in neuroimaging data with fractals

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During this lecture and workshop, we will introduce Fractal Space Curve Analysis (FSCA), a novel methodology for characterizing multidimensional data—particularly neuroimaging data—by examining their fractal properties. The core concept of FSCA is to transform multidimensional data (e.g., 2D, 3D, or 3+1D scans) into one-dimensional time series using space-filling curves (SFCs), primarily the Hilbert SFC. Detrended fluctuation analysis (DFA) is then applied to these series to quantify fractal features by extracting Hurst exponents.

To demonstrate the robustness of the method, we present FSCA tests conducted on artificially generated datasets, including two-dimensional fractional Brownian motion, Cantor sets, and Gaussian processes, as well as neuroimaging data. The results clearly show that FSCA effectively quantifies and distinguishes correlations in both stationary and dynamic two-dimensional images.

For neuroimaging data, we present results from the analysis of MRI scans, which include both healthy individuals and patients at various stages of dementia. A systematic decrease in the Hurst exponent was observed in Alzheimer's disease patients, particularly at longer scales, suggesting a reorganisation of brain structure toward greater variability as the disease progresses. Furthermore, FSCA-based features demonstrated promising performance when incorporated into machine learning classifiers for diagnostic tasks, such as distinguishing healthy controls from or AD patients and predicting mild cognitive impairment conversion to AD.

In the workshop portion practical information will be provided to enable participants to perform the analysis FSCA themselves.

Reference:

J. Grela, Z. Drogosz, J. Janarek, J.K. Ochab, I. Cifre, E. Gudowska-Nowak, M.A. Nowak, P. Oświęcimka, and D.R. Chialvo. Using space-filling curves and fractals to reveal spatial and temporal patterns in neuroimaging data. Journal of Neural Engineering 22 (2025) 016016.

Session 6: AI, Cognitive Neuroscience and Complex Brain Models

From statistical physics to machine intelligence.

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Understanding the neural basis of mental phenomena remains a great challenge. Statistical physics contributed to the development of attractor neural networks that are our best models linking mental states with the physical properties of the brain. Information (from senses and memory) is embedded in high-dimensional patterns of neural activity. It can be visualized by fMRI scans. Generative neural models based on diffusion processes resemble formation of brain patterns, illustrating associative aspects of thinking in large language models. Transitions between attractor states simulate chains of thought. Higher-level processes needed for different reasoning strategies are based on Good Old-Fashioned symbolic AI (GOFAI) that has achieved superhuman level in chess, go, and many other games. New autonomous-learning model architectures may lead to similar results in many real-world applications, including medicine. Large neural models (LLMs) internalize information in rich contexts, learning from text, spoken language, images, videos, and various signals. Augmented reality glasses provide additional source of visual and behavioral data. LLMs capable of associative thinking were scaled up to billions of neural network parameters, compressing and internalizing most of human knowledge stored in texts and multimedia form. Deeper understanding requires high-level abstractions from observations, and current systems are mostly approximating observations. Physics-informed systems can be first trained to respect constraints based on the laws of physics, before they can be successfully applied to predict complex real-world phenomena. Attractor network simulations show how temporo-spatial processing disorders can be related to properties of networks and individual neurons, and offer a neural interpretation of psychological phenomena.
How long human expertise will retain its value?

Session 6: AI, Cognitive Neuroscience and Complex Brain Models

Learning Capacity in Networks of Junctions with Memory

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Memory effects are a ubiquitous feature of nanoscale systems, arising in particular from resistive junctions that give rise to memristive behavior. In this work, we investigate the learning capacity of memristive networks, with a focus on nanowire and nanoparticle architectures. We discuss two examples of learning, e.g., two-phase and contrastive learning with resistive and memristive networks. We show that learning capacity can be characterized by the fixed points of network dynamics, which serve as attractors encoding stable computational states. This perspective naturally connects the analysis of memristive networks to algebraic geometry, where the fixed-point structure is captured by the Gröbner basis of polynomial equations. Thus, we establish a mathematical framework that links material-level memory dynamics to the emergent information-processing abilities of physical systems.

Coffee and Poster Session

Application of Avrami phase transition model to cellular carcinogenesis

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The nucleation and growth theory, described by the Avrami equation (also called Johnson–Mehl–Avrami–Kolmogorov equation), and usually used to describe crystallization and nucleation processes in condensed matter physics, was applied to cancer physics as Avrami-Dobrzyński Model. This approach assumes the transforming system as a DNA chain including many oncogenic mutations. Finally, the probability function of the cell's cancer transformation is directly related to the number of oncogenic mutations. This creates a universal sigmoidal probability function of cancer transformation of single cells, as observed in the kinetics of nucleation and growth, a special case of a phase transition process. The proposed model, which represents a different view on the multi-hit carcinogenesis approach, is tested on clinical data concerning gastric cancer, breast cancer and ovary cancer. Additionally, the model was tested on mice, which allows to help in the cancer risk prediction for population. The results also show that cancer transformation follows DNA fractal geometry.

Coffee and Poster Session

Quantum resetting in Szegedy Walk

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Szegedy quantum walks represent a generalization of discrete random walks to the quantum domain, finding broad applications in quantum computing. Recent studies have demonstrated that classical resetting mechanisms can accelerate the arrival of a particle at its target, even in the context of quantum walks. This poster presents an approach to introducing purely quantum resetting into Szegedy walks. Furthermore, it investigates how resetting affects key quantities characterizing the problem of reaching a selected vertex for various graph types, including hitting times and vertex occupation probabilities.

Coffee and Poster Session

Optimization of thin films in organic diodes using computer simulation

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Computer simulations were carried out to understand the processes that occur in organic light-emitting diode (OLED) devices at an atomic and macroscopic level. The main goal was to optimize the OLED structure by taking into account the transport of charge carriers, quantum efficiency and stability. The characteristics and morphology of subsequent layers and interlayer junctions were also examined, as was the exact relationship between the degree of layer interpenetration and the energy barrier for charge carriers, and the interaction between host-guest complexes in the emissive layer and charge transport properties. To overcome the difficulties associated with the different sizes and timescales of polymer systems, we propose developing efficient coarse-grained computer simulation methods. Simplifying macromolecular systems due to their complexity enables the study of morphology and the electroluminescence effect of large systems over sufficiently long timescales. We used the Dynamic Lattice Liquid model, a variant of the Monte Carlo method based on the concept of cooperative motion. The most demanding cases were performed on the ARUZ dedicated machine in the BioNanoPark in Łódź. A machine learning approach, most likely a neural network, was designed and trained on this data to predict promising combinations of experimental parameters and conditions. This enabled the simulation of phenomena occurring simultaneously for all molecules, significantly accelerating the calculations and enabling the study of systems consisting of millions of elements, as in real OLED layers.

Coffee and Poster Session

Inertia-induced mechanism for giant enhancement of transport generated by active fluctuations

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Active matter is one of the hottest topics in physics nowadays. As a prototype of living systems operating in viscous environments it has usually been modeled in terms of the overdamped dynamics. Recently, active matter in the underdamped regime has gained a place in the spotlight. Here we unveil another remarkable face of active matter. In doing so we demonstrate and explain an inertia-induced mechanism of giant enhancement of transport driven by active fluctuations which does emerge neither in the overdamped nor in the underdamped limit but occurs exclusively in the strong damping regime. It may be relevant not only for living systems where fluctuations generated by the metabolism are active by default but also for artificial ones.

Coffee and Poster Session

Force-Free Steering of Flocks via Spatially-Dependent Activity

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The **active Brownian particle** model can exhibit directed motion when subjected to **spatial gradients in activity**, such as light-induced motility in bacteria. In the absence of external forces, this rectification arises only in two or more dimensions. Here, we use computer simulations to study **Vicsek-like flocks** of aligning active Brownian particles moving through two-dimensional environments with geometrically modulated activity. We demonstrate how activity gradients and local alignment cooperate to enhance directed transport. By comparing these results with non-interacting models, we isolate and highlight the role of collective effects in this rectification process.

Coffee and Poster Session

Inertia Tames Fluctuations in Autonomous Stationary Heat Engines

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Thermodynamic uncertainty relations (TURs) provide fundamental constraints on the interplay between power fluctuations, entropy production, and efficiency in overdamped stationary autonomous heat engines. However, their validity in underdamped regimes remains limited and less explored. Here, we analytically and numerically study a physically realizable autonomous heat engine composed of two underdamped continuous degrees of freedom coupled to a two-level system. We show that this nonlinear setup can robustly violate TUR-based trade-offs by exploiting resonant coupling, effectively using one underdamped mode as an internal periodic drive. When this coupling is suppressed, the system recovers TUR-like bounds consistent with overdamped theory. Importantly, we demonstrate that the strongest suppression of current fluctuations occurs in a resonance regime that can be directly inferred from mean current measurements—a quantity typically much easier to access experimentally than fluctuations. Our results reveal new pathways to circumvent classical TUR constraints in underdamped systems and provide practical guidelines for designing efficient, precise microscopic engines and autonomous clocks.

Coffee and Poster Session

Flexopolarization and Landau–de Gennes theory of modulated nematic phases

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Modulated nematic phases, such as the twist-bend nematic (NTB) and splaybend nematic (NSB) phases, experimentally discovered within the last 15 years, are among the most intriguing liquid crystal phases due to their potential practical applications. A possible mechanism underlying the stabilization of these phases is flexopolarization-induced softening of the bend elastic constant. To investigate this mechanism, we employ the helicity-mode expansion of both the alignment tensor field Q and the polarization field P, with the goal of identifying global minimizers of the minimal-coupling Landau–de Gennes theory with flexopolarization. This theoretical approach was first proposed by Longa and Trebin 1 and has successfully explained the stability [2,3] and field-induced behavior [4] of the NTB phase. The primary objective of the present study is to identify all classes of phase diagrams exhibiting at most one-dimensional periodic structures that can be predicted by this theory. The helicity-mode expansion is utilized to systematically control approximations when modeling these structures. The most significant new result is the simultaneous identification of both the NTB and NSB phases within a single phase diagram, along with the characterization of possible phase transitions between these and other nematic phases.

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Coffee and Poster Session

Information Entropy in Mutating Viruses

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A large amount of information about the singular type of virus caused by SARS-CoV-2 during the COVID-19 pandemic has provided unique insights into the stochastic processes connected to mutations at the DNA level and changes in system entropy. Predictions made by biophysical Single Hit Target Models associate DNA damage with an increase in system entropy. However, it turns out that not all mutations exhibit the same nature. Using real-world data provided by the National Center for Biotechnology Information, it is evident that viruses, as complex systems, are capable of decreasing Shannon's entropy in the context of their DNA. The analysis of mutating viruses offers unique insights into evolving and self-adapting systems that are far from thermodynamic equilibrium. Naïve simulation methods, which assume complete randomness in the processes of mutation and selection, are not compatible with the observed phenomena. The existence of bifurcations, local maxima, and visible "flares" calls for the development of new and more complex models. With multiple examples demonstrating this observed trend (such as COVID-19, HIV, and influenza), and with both classical statistical methods and Bayesian robust regression confirming the existence of this trend, this could represent a significant step toward developing methods for predicting future mutations and the directions of viral evolution.

Coffee and Poster Session

Information dynamics of heart rhythm, repolarization and amplitudes time series in Long QT Syndrome

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Biological systems, such as the cardiovascular system, are governed by complex nonlinear dynamics arising from interactions within and between their components. From the perspective of statistical physics, metrics from information theory provide a powerful framework for quantifying couplings among physiological processes. In particular, entropy-based methods enable the detection of directional information flows between physiological time series.

This study investigates the information flow between heart rhythm and repolarization processes in patients with Long QT Syndrome (LQTS). Data from 195 LQTS patients (including subtypes LQTS1, LQTS2, and LQTS3) and 150 healthy controls were selected from the THEW database, focusing on nighttime Holter ECG recordings. From these signals, RR, QT, and DI intervals, as well as QRS and T-wave amplitudes, were extracted. After segmentation and detrending, signal stationarity was verified. Conditional entropies were estimated in bivariate and trivariate configurations using the ITS Toolbox developed by Luca Faes and collaborators. Out of 23 entropy-based variables, only those representing statistically significant information flow were retained.

Classification models using Random Forest (RF) and Support Vector Machine (SVM) were trained on the selected features to distinguish LQTS patients from healthy individuals. For RF, both accuracy and specificity were above 90%, while for SVM, accuracy, sensitivity, and specificity all exceeded 90%. These findings demonstrate that entropy-based metrics derived from ECG recordings can effectively capture the complexity of cardiac electrophysiology and support the development of automated diagnostic tools for arrhythmogenic disorders such as LQTS.

Coffee and Poster Session

Study of Particle Dynamics in a Conically Widening Channel

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Assessing the diffusion characteristics of tracer particles in complex environments, including soft matter and biological matter, yields valuable insights into material properties and biological processes. This is particularly evident in the transport of single molecules, viruses, and particles passing through natural and synthetic pores, which exhibit peculiar features that are the subject of intense theoretical and experimental research. Single nanopores are attracting increasing attention due to their potential use in nanofluidics, sensor technology, and information processing. In such systems, the observed diffusion is often anomalous and is characterized by non-linear growth of the mean squared displacement (MSD). A linear dependence of MSD on time is observed in the case of normal diffusion.
In this work, we show that variations in the geometry of the medium allow us to assess the effect of the structure of the medium on the transport of matter through it. We investigate the kinetics of spherical particles passing through a conical pore restricted by absorbing and reflecting boundaries from a wider to a narrower end and vice versa. We study the properties of diffusion as a function of particle size concerning pore width. Particles of different diameters are subjected to a random force. In addition to the mean squared displacement, we measure the mean and median of the first passage times. We show that the specific interplay of entropic forces and boundary conditions used to ensure the passage of events can explain the observation of effective subdiffusion in the tapered channel and effective superdiffusion in the widening channel. Furthermore, we study the diffusion of spherical particles in a conical widening channel (from a reflecting boundary to an absorbing one), focusing on the effects of deterministic drift and entropic forces.
The results show that the diffusion type depends on the drift strength. Without the drift, entropic forces induce superdiffusion; however, increasing drift strength shifts the system to standard diffusion and then subdiffusion.

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Coffee and Poster Session

Energy dependence of the long-term GCR variation by AMS02 data.

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Using measurements from the Alpha Magnetic Spectrometer AMS02 aboard the International Space Station, we have examined the long-term variations in galactic cosmic ray (GCR) proton fluxes in 2011–2018. The AMS02 data allow study of time profiles and the energy/rigidity dependence of the long-term GCR variations observed directly in space in a wide rigidity range, from ∼(1 - 100)GV. We have investigated the energy/rigidity dependence of the amplitude of the long-term GCR variations described by the power law fitting over the solar cycle in the period 2011-2018. For a physical interpretation, we have considered the relationship between the long-term GCR variations and solar wind plasma and other heliospheric parameters changeability.

Coffee and Poster Session

State-dependence in diffusion-controlled transport and stochastic resonance

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Most natural phenomena evolve through non-equilibrium pathways following non-linear dynamics involving the crossing of a potential energy barrier. During these processes the systems transit from one state to another. We intend to understand in detail the significance of these states, their positions, and associated intrinsic fluctuations. As these systems are inevitably subjected to environmental noise, there appears complexity in studying their behavior. We focus on analyzing the rate of diffusion-controlled transport in these complex systems under pertinent conditions. We implemented distinctions in the characteristics of the concerned states by altering their positions and the level of noise or diffusion coefficients linked to them. It has been observed that the variation of the reference point position and the diffusion coefficients have significant impacts on the rate. Our investigations unveil very important and critical aspects of the characteristic roles of the initial and final states in diffusion-controlled kinetics. We continued to develop an understanding of these fundamental transport phenomena where periodic force is involved. This is a particular scenario where the constructive interplay of noise and the non-linearity of the system comes into effect in the presence of appropriate conditions. The phenomenon is termed stochastic resonance. We explored the significance of the state dependence in stochastic resonance which manifests in many natural and designed processes, starting from climate systems to chemical reactions [1-3]. We developed a completely analytical theory in the adiabatic limit and a semi-analytical approach for the general case for stochastic resonance considering state-dependent diffusion. The theoretical findings are substantiated with numerical simulation results. The results of our studies not only enrich the fundamental understanding of diffusion-controlled kinetics but also indicate the paths to developing advantageous technologies based on optimizing the conditions of transport.

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Coffee and Poster Session

Cellular Curvature as a Mechanical Regulator of Tissue Morphogenesis

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The active vertex model is a widely used framework for studying mechanical properties, phase transitions, cell topology, and tissue organization in developmental biology. In this work, we extend the classical formulation by introducing a curvature energy term that captures bending at cell edges through interactions between neighboring vertices. By assigning different target curvature values to cells, we investigate how curvature influences both tissue phase behavior and cell morphology.
Our simulations demonstrate that cellular curvature can strongly modulate tissue mechanics: it can fluidize solid tissues, solidify fluid-like tissues, and give rise to heterogeneous intermediate states. These findings highlight curvature as a mechanical regulator, capable of reorganizing tissue architecture and dynamics. This approach opens new directions for understanding the role of membrane bending and geometric constraints in tissue morphogenesis.

Coffee and Poster Session

Emergent network motifs under increasing cognitive load

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Biological neural networks can efficiently solve cognitive tasks with different levels of complexity. However, we still lack understanding of how structural and functional features of these networks are affected by increasing the complexity of the goal function. This raises the following fundamental questions: What structural/functional network motifs drive success? How do these motifs change as cognitive demands increase? Can we predict or even engineer success by tuning these features? We address these questions by investigating the emergence of minimal, overrepresented neural network motifs in Artificial Neural Networks (ANNs) evolved via NeuroEvolution of Augmenting Topologies (NEAT). As the proxy for increasing cognitive load we use increasing velocity intervals in a modified version of the classic Atari game Pong. Using a fitness function that involves tracking, prediction and minimal complexity, we evolved three ensembles of ANNs with a goal to successfully play Pong with the varied maximum velocity of the Pong ball (Low, Medium and High velocity constraints). We found that the number of successful ANNs for the Medium ensemble was approximately two times larger than the number of successful ANNs for the Low and the High ensembles. The visual inspection of the High-Low ANNs solving the task confirmed the presence of repetitive exploitative behaviors whereas Medium ANNs consistently tracked the ball. Taking the intersection of all successful ANNs across the interpolation analysis and re-testing them produced nearly perfect solutions that work across the tractable spectrum. By combining Uniform Manifold Approximation and Projection (UMAP) and Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN), the structural feature vectors of the ANNs were identified and correlated with the success criteria across a broad interval of velocities. By linking neural topology evolution to computational complexity theory, this study offers an insight for understanding how structure emerges to meet the demands of increasing cognitive load.

Coffee and Poster Session

Solving the inverse problem of Turing patterns

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Patterns such as stripes, spots, and digit arrangements in animals emerge from multicellular organization driven by gene regulatory networks and intercellular signaling. In developmental biology, these processes can be modeled as reaction–diffusion systems, where intracellular gene interactions act as reactions and protein-mediated communication between neighboring cells is captured by diffusion. Turing's mechanism provides a powerful framework to explain how local gene activity translates into large-scale biological patterns.

However, the nonlinear nature of reaction–diffusion equations makes purely numerical simulations insufficient to address fundamental questions: Can distinct gene regulatory networks generate the same observed pattern? How robust are patterns to perturbations in initial conditions? How quickly and precisely do patterns form?

We address these questions by deriving explicit analytical formulas in the linear and weakly nonlinear regimes. First, we find a parametrization of the gene regulatory network that allows us to generate all possible Turing patterns with two morphogens. Second, we deduced an inequality showing that patterns with larger wavelengths take longer to form. Thirdly, we compute a formula for the final amplitude of the pattern, whose region of applicability is precisely where the pattern is the most robust to noise in the initial conditions. These results allow us to characterize pattern sensitivity, likelihood, and dynamics. To validate our approach, we compare the analytical predictions with numerical simulations across several well-studied models, showing strong agreement.

Taken together, our findings could help to identify regions of Turing space that provide most stable and reproducible biological patterns.

Coffee and Poster Session

Hitting Blinking Targets Under Stochastic Resetting

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The first hitting times of a stochastic process, i.e. the first time a process reaches a particular level, are of significant interest across various scientific disciplines, including biology, chemistry, and economics. We modify the standard setup by allowing the target to spontaneously switch between two states, either active or inactive, and investigate the distribution of first hitting times accrued while the target is active. For this setup, we provide closed formulas for the distribution of the first hitting time. Additionally, we can introduce stochastic resetting to the underlying process and, utilising our results, derive the formulas for the first time the active target is hit by the process under stochastic resetting. Interestingly, we show that resetting in this setup still leaves some memory; the system is no longer Markovian, which prevents a straightforward application of standard techniques. The analytical results are verified by Monte Carlo simulations of Langevin dynamics.

Coffee and Poster Session

EEG signal segmentation for assessing the time-course of brain response to stimuli

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Signal detected by electroencephalography (EEG) exhibits a power spectrum with a predominant $1/f$ component. As such, the signal is nonstationary. When EEG is applied to the study of cortical response to stimuli, the event-related potential (ERP) technique is commonly used.
It led to innumerable insights into the mechanisms of cognition. However, it has significant limitations:
A) it relies on averaging the EEG signal around the stimuli over many experimental trials; as such, it does not fully exploit the data's non-stationarity,
B) it requires careful pre-processing of the signals to ensure reliable results.

We propose an alternative technique utilizing an algorithm introduced by Camargo et al. (2011), which recursively divides the series into segments based on maximizing statistical distance between them.
We compare the original algorithm utilizing the KS-statistic with the potentially better-suited AD-statistic, and validate both variants on synthetic data.
We then validate the method's performance on standardized EEG recordings from the ERP CORE dataset and compare it with the ERP technique, including testing of the impact of pre-processing steps.

Session 7: Computational Models of Disease, Development and Evolution

Price of information in games of chance

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In the age of data-driven decision-making, understanding how to assign a fair price to information has become a pressing and complex challenge. Information, in the form of intangible data that can be traded in exchange of money, does not follow the standard supply-demand rules that govern tangible assets. We address this problem by developing a game-theoretic and statistical physics framework for pricing information in games of chance. Specifically, we analyze a setting in which players bet on the outcome of an underlying stochastic process whose statistical properties are unknown, and receive a reward if the bet is successful. One or more players possess privileged information about the process, derived from past observations. Using tools from Bayesian game theory and expected utility maximization, we quantify the financial value of this information by computing equilibrium strategies and the range of fair transaction prices when the informed player sells part of their data to a competitor instead of using it exclusively to exploit their 'edge' in the game. Our model reveals a rich landscape of regimes—symbiotic, competitive, and even predator-prey—depending on the quality of information shared and the number of players involved. We further incorporate volatility aversion into player preferences, capturing realistic behaviors in uncertain environments and highlighting the dependence on the length of the string of data exchanged. This work lays the foundation for a theory of data valuation grounded in principles of both economics and statistical mechanics, with implications for digital marketplaces, algorithmic trading, and the broader study of informational asymmetry.

Session 7: Computational Models of Disease, Development and Evolution

Discontinuous Phase Transitions in Opinion Dynamics: The Role of Quenched Disorder

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Discontinuous phase transitions are a desirable phenomenon in models of opinion dynamics because they capture abrupt shifts in collective behavior, critical mass effects, and social hysteresis. These transitions help explain real-world phenomena such as political polarization, the persistence of vaccine hesitancy, and delayed responses to policy changes. Therefore, identifying the conditions that lead to such transitions is crucial for understanding real-world opinion dynamics. In our previous work, we showed that replacing an annealed (situation-based) approach with a quenched (personality-based) approach in the multistate q-voter model with anticonformity on a complete graph can induce a discontinuous phase transition. This is surprising, as quenched disorder is typically expected to smooth out or eliminate such transitions. This puzzling result immediately raised the question of whether this effect can be observed only on the complete graph or also on other structures. In this talk, I will address this question by presenting completely new results, which I hope will intrigue the audience as much as they intrigued us.

Session 7: Computational Models of Disease, Development and Evolution

(Deep) Learning to Predict Complex Market Dynamics

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Financial markets are data-rich systems where prices and their dynamics emerge from the continuous interaction of many agents. In this talk, I present a framework that combines deep learning with ideas from statistical physics to understand and predict short-term price movements in modern electronic markets. At the core of this framework is the Limit Order Book (LOB)—a high-frequency, tabular data structure that reflects the evolving state of supply and demand. From a machine learning perspective, modelling LOBs poses a significant challenge, sharing many of the difficulties seen in deep learning on tabular data, where standard architectures often underperform compared to simpler models. Yet, the fine-grained and structured nature of LOB data offers unique opportunities to uncover latent patterns not easily accessible through traditional approaches.

Using data from NASDAQ-traded stocks, we examine how microstructural features—such as tick size and liquidity—influence predictability, and we evaluate models not only by their statistical accuracy, but by the feasibility of trading strategies they enable. Finally, I introduce a hybrid approach that augments deep learning with network-based representations of LOBs, capturing spatial and temporal dependencies across price levels. This perspective, inspired by statistical physics and complex systems theory, sheds light on how information flows and decays in high-frequency markets. Moreover, the proposed methodology is general and may be applied to other structured, dynamical systems beyond finance.

Session 7: Computational Models of Disease, Development and Evolution

Tracer particles in correlated media - fluctuations and memory-induced effects

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In the linear overdamped Langevin equation, the effect on a mesoscopic particle (e.g., a colloid) of its collisions with the molecules of the surrounding medium is described by instantaneous friction accompanied by a random force modeled by Gaussian white
noise, yielding a Markovian dynamics of the particle. Such a description hinges on the assumption of time-scale separation, i.e., that the motion of the molecules occurs on
time-scales much shorter than the one at which the motion of the particle is described.

Media undergoing a second-order phase transition exhibit collective fluctuations characterized by long-range correlations across the distance set by the correlation length ξ, and macroscopic relaxation times, comparable with the typical time-scale of the motion of a colloidal particle. The coupling between a tracer particle and such slow collective fluctuations breaks time-scale separation and leads to an effective non-Markovian dynamics of the colloid.

We investigate the dynamics of a colloidal particle in a harmonic trap coupled with a fluctuating Gaussian field with a tunable correlation length ξ following relaxational dynamics. The proposed model allows us to analytically describe emergent memory effects and the interplay between stochasticity and fluctuation-induced critical Casimir forces, both in- and out-of-equilibrium. Among them, we demonstrate the emerging memory-induced term in the time-correlator of the particle position, its behavior in the bulk and in the presence of a wall. Also, we derive a backwards motion of a particle released from a trap moving with constant velocity through a near-critical medium.

Session 7: Computational Models of Disease, Development and Evolution

Emergent noise control mechanism stabilizing gap gene pattern in Drosophila embryo

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In developing embryo cells determine their fate by reading diffusing chemical signals called morphogens. Yet, as the initially imposed morphogens wear out, the corresponding pattern of gene expression remains self-sustained in cells. In order to achieve this, the pattern-maintaining mechanism must be robust enough to overcome significant amounts of noise, inherent to the gene expression dynamics and the competition between interacting genes. The system in which this problem is studied is the 'four gap gene' pattern, forming around cycle 13 of Drosophila embryo development. In this talk, I will show how massive, molecular-level accurate simulations of the entire embryo [1] were combined with a recently found exact solution in the theory of pattern stabilization [2]. This revealed the emergent noise-control mechanism, providing both a qualitative explanation for the pattern longevity as well as the quantitative prediction of the highest-stability regime, in which the pattern survival time increases by two orders of magnitude. The study provides insight into the principles of robust patterning systems design.

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Session 8: Aspects of Statistical Physics

Opportunities and challenges in statistical mechanics: The fluctuationdissipation theorem and its limitations

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The fluctuation-dissipation theorem is the main tool for obtaining the response of a physical system. However, FDT fails in many situations (see 1 for review), such as phase transitions, spin glass, anomalous diffusion, and growth phenomena. We develop the hypothesis that the dynamics of a given system may lead to a fractal dimension d_f different from the original spatial dimension d. This phenomenon is more easy to observe near a phase transition. We also speculate how the response function might be sensitive to this change in dimensionality. We discuss how this phenomenon appears in phase transition and growth phenomena [2-7]. We show that the Fisher exponent η

$$\eta = d - df$$

is the deviation from the integer dimension. Thus we determine exactly the fractal dimension df for the Ising model in two dimensions as $d_f = 7/4$ and we validate it via computer simulations.

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Session 8: Aspects of Statistical Physics

Lukasiewicz logic and Tsallis entropy connected with free projections in the free and conditionally free probability

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In my talk we consider the following topics:

1.Free and C-free probaility and completely positive maps.

2.Free independent projections as a model of Jozef Lukasiewicz n-valued logic , $n > 2$ and also model of continuous logic of Lukasiewicz-Tarski.

3.Main Theorem: : If q is real number and x, y are from interval $(0, 1)$, then the Tsallis entropy is defined as

$$T_q(x, y) = [x^{1-q} + y^{1-q} - 1]_+^{1/(1-q)}.$$

Then we have: If $\mathbf{P}$ and $\mathbf{Q}$ are free independent in some probability space $(\mathbf{A}, \text{tr})$ with trace tr state on $\mathbf{A}$, and tr$(\mathbf{P}) = x$, tr$(yQ) = y$, then tr$(\mathbf{P^Q}) = T_0(x, y)$, if $\mathbf{P}$ and $\mathbf{Q}$ are Boolean independent, then tr$(\mathbf{P^Q}) = T_2(x, y)$ and relations with Dagum distributions, which are called log-logistic distributions in many statistics models.

If $\mathbf{P}$ and $\mathbf{Q}$ are classical independent then tr$(\mathbf{P^Q}) = T_1(x, y) = \lim$ $T_s(x, y)$, as s tends to 1.

Here the projection $\mathbf{P^Q}$ is the smallest projections on the closed linear span of Im$(\mathbf{P})$ and Im$(\mathbf{Q})$. The generalizations of cases of Tsallis entropy T_q, for q in (0,1) we will use conditionally free independent projections.

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Session 8: Aspects of Statistical Physics

Integral formulation of run-and-tumble particles in simple confinements

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In this talk, we present an integral equation formulation of run-and-tumble particles (RTPs) under two types of confinement: between parallel walls and within a harmonic potential. This reformulation allows us to obtain exact analytical results that are not accessible through the standard Fokker-Planck differential equation approach. A second objective is to draw analogies between the RTP model and other well-known models in statistical mechanics. Finally, we seek to understand why exact solutions are attainable in certain spatial dimensions but not in others.

Session 8: Aspects of Statistical Physics

Polymer chains under oscillatory force in solvents of variable quality

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Polymers are key materials in soft condensed matter with diverse applications. Recently, significant attention has been given to understanding the micromechanical behavior of single macromolecules under applied forces. Using molecular dynamics, we examined how constant and periodic forces affect polymer chain conformations in dilute solutions, modeled for good and poor solvents. We systematically calculated the projection of the end-to-end vector in the force direction as a function of the applied force. This analysis led to the construction of force-extension diagrams, which revealed conformational transitions of polymers from a globular state to an extended chain. Analysis of hysteresis loops for periodic forces showed that longer force periods allowed more time for the system to respond, resulting conformational reorganization. These results were compared with analytical solutions of the Rouse model under periodic perturbation and scaling laws, providing a valuable benchmark and deeper insight into the observed dynamics. We also characterized the relationship between dissipated energy and the frequency of the applied sinusoidal stretching force. These findings provide new insights into the mechanical behavior of polymer chains under oscillatory forces, enhancing our understanding of their dynamic properties and potential applications.

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Useful Information

Emergency calls

Ambulance	**999**
Fire brigade	**998**
Police	**997**
Emergency number (mobile phone)	**112**
City Guard	**986**
Medical information	**12 661 22 40**
Toxicological Intervention in Emergency Situations	**12 411 99 99**
International Code for Poland	**0048**

Exploring Kraków & Cultural Events

- City Internet Platform – www.krakow.pl/english
- Travel Guide – www.krakow.travel/en

Public transport

For buses and trams, there is a public transport trip planner: Jak dojadę, which can be installed on a mobile phone from Google Store (Android) or App Store (iOS). With this service, you can get real-time directions from your location to any destination.

Tram and bus tickets are available from the ticket machines in all trams and buses (payment can be done by either coins or contactless debit card). You may also buy tickets in the stationary machines. Two most popular ticket types for one person are: 20 min. bus and tram journeys (4.00 PLN) and 60 min. bus and tram journeys which is also a single line (6.00 PLN) ticket. All tickets, regardless of the point of purchase, must be validated immediately after boarding or after purchase in the ticket machine (inside tram/bus).

Taxi

Icar	(+48) 12 653 5555
Barbakan Taxi	(+48) 12 196 61
Mega Taxi	(+48) 12 196 25
Radio Taxi 919	(+48) 12 191 91
Radio Taxi Wawel	(+48) 12 196 66

Notes

Sun 14/09		Mon 15/09		Tue 16/09		Wed 17/09	
		9:00	Marek Kimmel	9:00	Mária Ercsey-Ravasz	9:00	Pierpaolo Vivo
		9:30	Monika Kurpas	9:30	Paweł Oświęcimka	9:30	Katarzyna Sznajd-Weron
		10:00	Marcin Zagórski	10:15	Workshop 1	10:00	Silvia Bartolucci
		10:30	Krzysztof Fornalski			10:30	Marcin Pruszczyk
						10:50	Maciej Majka
		10:50	Coffee Break	12:00	Coffee Break	11:10	Coffee Break
11:30	Elena Agliari	11:30	Janusz Hołyst	12:30	Workshop 2	11:30	Fernando Oliveira
12:00	Thiparat Chotibut	12:00	Łukasz Kuśmierz			11:50	Marek Bożejko
12:30	Taro Toyoizum	12:30	Raoul-Martin Memmesheimer			12:10	Derek Frydel
13:00	Miłosz Panfil	13:00	Moupriya Das			12:30	Bogumila Szostak
		13:20	Szymon Starzonek				
13:20	Lunch Break	13:40	Lunch Break	14:00	Lunch Break	13:00	Lunch Break
15:00	Greg Huber	15:00	Roman Jaksik	15:00	Włodzisław Duch		
15:30	Jeremi K. Ochab	15:30	Benjamin Lindner	15:30	Francesco Caravelli		
16:00	Marcelo J. Rozenberg	16:00	Apurba Biswas	16:00	Poster session		
16:30	Antoine Naert	16:20	Tadeusz Kosztołowicz	18:00 –	Gala Dinner		
16:50	Wojciech Tarnowski						
17:10	Get-together						