Complex Spreading Phenomena: From Bacteria to Innovations

826. WE-Heraeus-Seminar

12 – 17 January 2025

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 826. WE-Heraeus-Seminar:

Spreading is an omnipresent phenomenon which plays either negative or positive role, depending on what is spreading, an invasive pathogen or a new technology. There are many facets of spreading that have been studied in different fields, ranging from ecology and epidemiology to chemistry and quantum physics.

Diffusion and random walks are two main paradigms that are usually used to design a model for a given spreading phenomenon. However, most of the natural spreadings are not just territorial expansions of point-like objects driven by a couple of equations. Spreading agents are able, for example, to modify their strategies, communicate with each other, fight enemies, adapt to the environment, and produce offspring. In other words, spreading agents have their own internal dynamics (or, sometime, intelligence) which is coupled to the territorial expansion and substantially affects the appearing space-time pattern.

How this complexity can be captured with mathematical models? The idea of our workshop is to bring together experts dealing with complex spreading phenomena – on different space-time scales – in order to exchange ideas and figure out new approaches to modeling these phenomena. It will involve researchers working on diffusion and random walk processes, experts in nonlinear dynamics, biophysicists, and sociologists.

Scientific Organizer:

Prof. Dr. Raffaella Burioni	Università di Parma, Italy E-mail: raffaella.burioni@unipr.it
Prof. Sergiy Denysov	Oslo Metropolitan University, Norway E-mail: sergiyde@oslomet.no
Prof. Dr. Vasily Zaburdaev	Universität Erlangen-Nürnberg /Germany E-mail: vasily.zaburdaev@fau.de

Introduction

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday morning

Program

Program

Sunday, 12 January 2025

17:00 – 21:00	Registration	
from 18:00	*BUFFET SUPPER and informal get-together*	

Monday, 13 January 2025

08:00	*BREAKFAST*	
09:00	Scientific organizers	**Opening**
09:15 – 10:00	Shlomi Reuveni	**Sokoban: a model for percolation with obstacle-pushing**
10:00 – 10:45	Jona Kayser	**Evolution of therapy resistance in spreading cellular populations**
10:45 – 11:15	*COFFEE BREAK*	
11:15 – 12:00	Anupam Kundu	**Hydrodynamics and super-diffusive spreading of heat in one-dimension**
12:00 – 12:45	Stas Burov	**Disorder-induced anomalous mobility enhancement in confined geometries**
12:45	*LUNCH*	

Program

Monday, 13 January 2025

14:30 – 15:15	Alessandro Vezzani	**Big jump principle in physical modelling**
15:15 – 16:00	Vittorio Loreto	**Exploring the adjacent possible: Play, anticipation, surprise**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 18:00	Olivier Bénichou	Colloquium: **Universal exploration dynamics of random walks**
18:30	*DINNER*	

Program

Tuesday, 14 January 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Vittoria Sposini	**Subordination processes for non-Gaussian diffusion**
09:45 – 10:30	Carsten Beta	**Movement strategies of a polarly flagellated swimmer in complex environments**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Franziska Lautenschläger	**Search phenomena in immune cells**
11:45 – 12:30	Oskar Hallatschek	**The sensitivity of epidemic spreading to noise and long-range dispersal**
12:30	*LUNCH*	
14:30 – 15:00	Maryam Lotfigolian	**Routing of ticket control teams in an urban transportation network as an optimization problem: A quantum annealing approach**
15:00 – 15:30	Marco Mancastroppa	**The role of higher-order hierarchical structures in complex spreading processes**
15:30 – 16:00	Javier Cristín Redondo	**Understanding information propagation in insect swarms**
16:00 – 16:30	*COFFEE BREAK*	

Program

Tuesday, 14 January 2025

16:30 – 17:15	Ralf Metzler	**Non-Gaussianity and varying scaling exponents in long-range dependent motion**
17:15 – 17:45	Robert Großmann	**Active colloidal transport by motile cells**
18:00	*DINNER*	
19:00 – 21:00	**Poster session I**	

Program

Wednesday, 15 January 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Peter Hänggi	**Thermodynamics and its ensembles: Do we really understand the old stuff?**
09:45 – 10:30	Antonio Politi	**Heat transport in classical systems: a review of open problems**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Christina Kurzthaler	**Intermittent transport phenomena in active matter systems**
11:45 – 12:30	Samir Suweis	**The emergence of cooperation from shared goals in the governance of common-pool resources**
12:30	*LUNCH*	
14:30	**Excursion**	
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 16 January 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Erwin Frey	**Sonic swarms: Acoustic control in active matter**
09:45 – 10:30	Pedro Lind	**From physics to health and AI with eye-tracking data analysis**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Eli Barkai	**Packets of diffusing particles exhibit universal exponential tails**
11:45 – 12:30	Natasa Conrad	**The mathematics of complex spreading: From past to present social systems**
12:30	*LUNCH*	
14:30 – 15:00	Bara Levit	**Proteins: An equation of state**
15:00 – 15:30	Pedro Lencastre E Silva	**Distinguishing between Lévy and intermittent strategies in foraging dynamics**
15:30 – 16:00	Talia Baravi	**Solutions of first passage times problems: A bi-scaling approach**
16:00 – 16:30	*COFFEE BREAK*	

Program

Thursday, 16 January 2025

16:30 – 17:15	Marc Timme	**Dynamic perturbation spreading in networks**
17:15 – 17:45	Kristian Olsen	**Intermittent active motion for enhanced spatial exploration**
18:00	*DINNER*	
19:00 – 21:00	**Poster session II**	

Program

Friday, 16 January 2025

08:00	*BREAKFAST*	
09:00 – 09:45	Igor Sokolov	**Homogenization problems for generalized Langevin equation: The bath always wins**
09:45 – 10:30	Katja Taute	**Bacterial spreading in complex environments, from individuals to populations**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Davide Bernardi	**Landscape and environmental heterogeneity support coexistence in competitive metacommunities**
11:30 – 12:00	Scientific organizers	**Seminar closing**
12:00	*LUNCH*	

End of the seminar

Departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Posters

Jan Albrecht	**Likelihood-based inference for heterogeneous motile particle ensembles**
Fidel Álvarez-Murphy	**Proliferation dynamics in a mechanical model of cell collectives**
Alexander Antonov	**Inertial active matter governed by Coulomb friction**
Maxence Arutkin	**Influence of stochastic parameters on spreading dynamics**
Alberto Bassanoni	**Rare events and single big jump effects in Ornstein-Uhlenbeck processes**
Shailendra Bhandari	**Modeling eye gaze trajectories using GANs and Markov models**
Julien Brémont	**Propagator and persistence exponents of self-interacting Random Walks**
Yurii Bystryk	**Survival probability for a run-and-tumble particle with an arbitrary flight time distribution**
Adamo Cerioli	**Pedestrian fluxes in confined geometric networks: entropic measures and robustness of accessibility in a university campus**
Subhadip Chakraborti	**Hydrodynamic transport and clustering in cellular aggregates driven by contractile forces**
Agniva Datta	**Dynamics of intermittently self-propelled particles**
Aleksandar Davidov	**Routing of ticket control teams in an urban transportation network as an optimization problem: A quantum annealing approach**
Lucianno Defaveri	**Striking universalities in dynamical observables**

Posters

Jesus Mauricio Encinas Riveros	**A stochastic model for a competition of two microbial species with public-good production controlled by quorum-sensing**
Rosa Flaquer-Galmés	**First-passage time of a Brownian searcher with stochastic resetting to random positions**
Omer Hamdi	**Laplace’s first law of errors applied to diffusive motion**
Tommer D. Keidar	**Universal linear response of the mean first-passage time**
Kristina Maier	**Hybrid models for large scale infection spread simulations**
Alonso Martínez Cisneros	**Modelling opinion dynamics under the impact of influencer and media strategies**
Soham Mukhopadhyay	**Modeling host-pathogen interactions: infection as a population dynamics problem**
Soeren Nagel	**Co-evolving networks for opinion and social dynamics in agent-based models**
Arthur Plaud	**Exploration dynamics of 2 random walkers and competition in foraging**
Ion Santra	**Universal winding properties of chiral active particles**
Itamar Shitrit	**SOKOBAN random walk on the Bethe latiice**
Arash Soleiman Fallah	**Similarities between waves in phononic metamaterials and knowledge dissemination**
Leo Tarbouriech	**Multi-scale modeling of the chromatin fiber: coupling biophysics and optogenetics**
Mingqi Yan	**Stochastic bubble dynamics in phase-separated scalar active matter**

Abstracts of Talks

(in alphabetical order)

Solutions of First Passage Times Problems: A Bi-Scaling Approach

Talia Baravi[1], David A. Kessler[2], and Eli Barkai[1]
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The study of first passage times (FPTs) for diffusing particles reaching target states is foundational in numerous practical applications, including diffusion-controlled reactions. In large systems, FPT statistics exhibit a bi-scaling behavior, challenging the conventional use of a single time scale. In this work, we introduce a bi-scaling theory for the probability density function of FPTs in confined compact processes, applicable to both Euclidean and fractal domains and across diverse geometries. Our approach employs two distinct scaling functions: one capturing initial dynamics in unbounded systems at short times, and the other sensitive to finite-size effects at long times. The combined framework provides a comprehensive expression for FPT statistics across all time scales, offering new insights into compact search problems.

By deriving these scaling functions, we reveal the generality of the framework, demonstrating its applicability to eight distinct models, including scenarios with and without external force fields, active and thermal settings, and systems under resetting where non-equilibrium steady states emerge.

Eli Barkai

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Packets of diffusing particles exhibit universal exponential tails

Brownian motion is a Gaussian process described by the central limit theorem. However, Laplace-like exponential decays of the positional probability density function $P(x,t)$ of packets of spreading random walkers, were observed in numerous situations that include glasses, live cells, and bacteria suspensions. Using large deviation theory we show that such exponential behavior is generally valid in a large class of problems of transport in random media both for systems with quenched disorder [1] and for the continuous time random walk [2, 3]. While this behaviour is universal, when the jump size distributions are sub-exponential, we find a transition to the regime of the big jump principle.

References

[1] L. Defaveri and E. Barkai *Diffusion in Quenched Random Environments: Reviving Laplace first law of errors* (unpublished)

[2] E. Barkai, S. Burov *Packets of diffusing particles exhibit universal exponential tails* **Physical Review Letters 124**, 060603 (2020).

[3] O. Hamdi, S. Burov, and E. Barkai *Laplace's first law of errors applied to diffusive motion* **Eur. Phys. J. B** (2024) 97:67

Universal exploration dynamics of random walks

Léo Régnier,[1] Maxim Dolgushev,[1] S. Redner,[2] and Olivier Bénichou[1]

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The territory explored by a random walk is a key property that may be quantified by the number of distinct sites that the random walk visits up to a given time. We recently introduced a more fundamental quantity, the time τ_n required by a random walk to find a site that it never visited previously when the walk has already visited n distinct sites, which encompasses the full dynamics about the visitation statistics. To study it, we develop a theoretical approach that relies on a mapping with a trapping problem, in which the spatial distribution of traps is continuously updated by the random walk itself. Despite the geometrical complexity of the territory explored by a random walk, the distribution of the τ_n can be accounted for by simple analytical expressions. Processes as varied as regular diffusion, anomalous diffusion, and diffusion in disordered media and fractals, fall into the same universality classes.

Landscape and environmental heterogeneity support coexistence in competitive metacommunities

Davide Bernardi[1,2], Giorgio Nicoletti[3,4], Prajwal Padmanabha[1,5], Samir Suweis[1], Sandro Azaele[1,2], Andrea Rinaldo[1,4], Amos Maritan[1,2]

[1]University of Padova, Padova, Italy, [2]National Biodiversity Future Center, Palermo, Italy, [3]International Centre for Theoretical Physics, Trieste, Italy, [4]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, [5]University of Lausanne, Lausanne, Switzerland

Classical models in theoretical ecology often assume that the structure and extent of landscapes can be neglected. In contrast, metacommunity models describe the evolution of interacting species within spatially extended, structured environments. However, these models are mostly phenomenological and lack a clear connection to the underlying ecological processes. Furthermore, because they incorporate both local interactions and spatial effects, analytical solutions are rare and typically confined to simplified cases.
Here, we present a spatial metacommunity model in which the spatiotemporal evolution of competitive species is explicitly derived from fundamental ecological processes, including offspring production, death, diffusion in a multilayer network, and colonization [1].

Using methods from the statistical physics of disordered systems, we derive comprehensive analytical insights into species survival and coexistence in fragmented landscapes. Specifically, we identify global trade-offs between colonization and extinction processes that are critical for coexistence, emphasizing the role of spatial heterogeneity as a key requirement for stable biodiversity. When the topology underlying colonization is homogeneous, the landscape must exhibit heterogeneity to support coexistence [1]. Conversely, when quenched randomness is incorporated into the colonization dynamics, coexistence becomes possible even in homogeneous landscapes. Notably, this latter case supports the coexistence of both rare and abundant species, aligning with observed species-abundance distributions in real-world ecosystems. By fitting our theory to empirical data, we provide a novel interpretation of the conditions necessary for the coexistence of competing species. This framework enhances our understanding of the essential interactions between habitat structure, dispersal dynamics, and biodiversity.

[1] P. Padmanabha*, G. Nicoletti*, D. Bernardi*, S. Suweis, S. Azaele, A. Rinaldo, A. Maritan, Proc. Natl. Acad. Sci. U.S.A. 121 (44), e2410932121 (2024)

The mathematics of complex spreading: From past to present social systems

<u>N. Djurdjevac Conrad</u>

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Human mobility was a key driver of cultural and technological exchange in prehistoric times, influencing the spread of innovations and shaping societal development. In ancient societies, mobility was driven mainly by environmental influences, such as resource scarcity, environment suitability and climate change. To explore this process, we developed an agent-based model (ABM) that can simulate human movement in response to environmental conditions, and provide insights on ancient mobility patterns and their impact on cultural evolution [1,2]. In this talk, I will introduce this model and show how it can be applied on empirical data from Central Africa, spanning 120 000 years, highlighting how environmental changes may have influenced societal dynamics and cultural development. Additionally, I will provide a perspective on how similar models can be adapted to study social dynamics in modern societies, such as the spread of ideas and opinions in online social media networks [3,4].

References

[1] J. Zonker, C. Padilla-Iglesias and N. Djurdjevac Conrad. Royal Society Open Science, **10**(11), (2023)

[2] N. Djurdjevac Conrad, L. Helfmann, J. Zonker, S. Winkelmann and Ch. Schütte. EPJ Data Science, **7**(24), (2018)

[3] L. Helfmann, N. Djurdjevac Conrad, P. Lorenz-Spreen, Ch. Schütte, Scientific Reports, **13**(19375), (2023)

[4] N. Djurdjevac Conrad, N. Quang Vu, S. Nagel. Chaos **34**(093116), (2024)

Understanding information propagation in Insect Swarms

J. Cristín[1,2], **I. Giardina**[3,2], **M. Veca**[3], **T. S. Grigera**[2,4] **and A. Cavagna**[2,3]

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Collective behavior is a ubiquitous phenomenon across biological systems, ranging from cells organizing into tissues to bird flocks and human crowds [1]. In these systems, local interactions among individuals not only give rise to emergent collective organization but also serve as pathways for propagating information throughout the group. This information flow can play a critical evolutionary role, such as facilitating predator evasion or maintaining group cohesion during migration. As a result, understanding how such interactions drive collective behavior and information spreading has become a focal point of recent research, inspiring the development of physical models to capture their essential features.

In this work, we focus on a specific biological system: midges swarms. Using field-collected experimental data, the analysis of spatiotemporal correlations reveals that, despite the absence of net movement or macroscopic order, the correlation length scales with system size [2]. This scale-free behavior suggests that insect swarms operate near a critical point, where information spreading is optimized. Assuming the dynamic scaling hypothesis, z is the dynamic critical exponent, linking space and time to describe how information propagates within the system at criticality.

The Vicsek model, one of the most widely used frameworks for studying collective motion, fails to reproduce the experimentally observed dynamic critical exponent in insect swarms. In contrast, our simulations of the Inertial Spin Model (ISM)—which incorporates inertia into the dynamics, with the Vicsek model representing its overdamped limit—successfully capture the experimental exponent [3]. Furthermore, a coarse-grained field theory study identifies the fundamental ingredients necessary to produce different values of the dynamic critical exponent z. This analysis highlights the mechanisms intrinsic to the ISM, absent in the Vicsek model, that enable it to reproduce the experimentally observed information propagation (dynamic critical exponent), offering new insights into the dynamics of collective behavior [4].

References

[1] Vicsek, T. and Zafeiris, A. *Phys. Rep.* **517**, 3-4 (2012).
[2] Cavagna, A., Conti, D. *et al. Nat. Phys.* **13**, 914–918 (2017).
[3] Cavagna, A., Cristín, J. *et al. J. Phys. A: Math. Theor.* **57** 415002 (2024).
[4] Cavagna, A., Di Carlo, L. *et al.*. *Nat. Phys.* **19**, 1043–1049 (2023).

Sonic Swarms: Acoustic Control in Active Matter

Erwin Frey
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This talk explores a critical question at the intersection of living and synthetic systems: how do simple agents, through information processing, exhibit complex, collective behaviours? By investigating acoustic interactions in self-propelled active matter, we reveal diverse self-organized structures that demonstrate key emergent functionalities, including phenotype robustness, collective decision-making, and environmental sensing. The ability to monitor and manipulate these systems using sound makes acoustic interactions a promising avenue for technological applications. These findings offer new insights into the design principles of functional active matter and represent a significant step toward developing cybernetic microrobotic systems.

Active Colloidal Transport by Motile Cells

R. Großmann[1], L.S. Bort[1], V. Lepro[1], S.S. Panah[1],
R. Metzler[1,2], and C. Beta[1,3]

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The erratic motion of Brownian particles, agitated by collisions with the surrounding fluid molecules, is the paradigm of random colloidal transport in a passive environment. In this talk, we describe the transport of polystyrene beads whose motion is actively driven by cells via direct mechanical contact [1-3]. We use the amoeba *Dictyostelium discoideum* as a model organism for the migration of neutrophils and, in general, for actin-driven motility of adherent eukaryotic cells.

We will first discuss the stochastic dynamics of a single cell-cargo pair, particularly focusing on the existence of an optimal cargo size that enhances the diffusion of the load-carrying cells, even exceeding their motility in the absence of cargo [1], and estimate the active forces exerted by cells to move colloids [2]. Afterwards, we present the collective transport of micron-sized particles on a monolayer of motile cells [3]. The transport of colloids shows a crossover from superdiffusive to normal-diffusive dynamics. The particle displacement distribution is distinctly non-Gaussian even at macroscopic timescales exceeding the measurement time. We obtain the distribution of diffusion coefficients from the experimental data and introduce a model for the displacement distribution that matches the experimentally observed non-Gaussian statistics. We argue why similar transport properties are expected for many composite active matter systems.

These results can provide the basis for the future design of cellular microcarriers and for more advanced transport tasks in complex, disordered environments, e.g. tissues.

References

[1] V. Lepro, R. Großmann, S.S. Panah, O. Nagel, S. Klumpp, R. Lipowsky, and C. Beta, *Phys. Rev. Applied,* **18**, 034014 (2022)
[2] S.S. Panah, R. Großmann, V. Lepro, and C. Beta, *Small,* 202304666 (2023)
[3] R. Großmann, L.S. Bort, T. Moldenhawer, M. Stange, S.S. Panah, R. Metzler, and C. Beta, *Phys. Rev. Lett.,* **132,** 088301 (2024)

Thermodynamics and its ensembles: Do we really understand the old stuff?

Peter Hänggi

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The talk addresses a number of subtleties in the application of the powerful concept of equilibrium thermodynamics. First, it is important to emphasize that conventional thermodynamics rests on the pillar that the coupling of the system to its environment(s) is (are) limited to *very weak coupling*. The theory then becomes a powerful tool through the use of ensembles and their corresponding dimensionless (!) partition functions Q(....). Familiar to practitioners of statistical mechanics are the microcanonical (E,V,N) ensemble with Q:= Q(E,V,N), the three isothermal ensembles, i.e. the *canonical* ensemble Q:= Q(**T**,V,N), the *grand canonical ensemble* Q:= Q(**T**,V,**μ**), and the *isothermal-isobaric* ensemble with Q:= Q(**T**,**p**,N). In fact, there are 8 such ensembles [1,2] with corresponding thermodynamic functions/potentials. Apart from these isothermal-isobaric ensembles, there are less known ones such as the isoenthalpic (H,p,N)-ensemble, the iso-Hill (L,V,μ)-ensemble with energy L:= E - μN and the iso-Ray (R,p,μ)-ensemble with energy R= H - μN [1].
However, a particularly intriguing situation arises with the so-called pressure-temperature (**T**,**p**,N) ensemble, which inherently requires a *fluctuating* system volume V, which is of central importance in practice at constant pressure, but which has led to a plethora of still controversial questions. The crux of the matter is that volume V is not a generic mechanical quantity, which in turn leads to these still open questions [2]. Other subtleties arise with the role of finite system sizes with N particles away from its true macroscopic limit. This leads to the violation of the Gibbs-Duhem relation and thus to the violation of the homogeneity property of the thermodynamic functions.
Even more important issues (classical or quantum) arise for systems with a finite system-environment coupling strength. Thermodynamic consistency in obeying all the Grand Laws of Thermodynamics [3, 4] yields thermodynamic functions such as internal energy, entropy, etc., which take on expressions that are manifestly different from the usual textbook results known for weak coupling. These finite-strength thermodynamic functions in turn assume a non-trivial dependence on the coupling strength and system parameters such as temperature, etc., which are encoded in a so-called **Hamiltonian operator/function of mean force** [4].

References

[1] H.W. Graben & J.R. Ray, *Eight physical systems of thermodynamics, statistical mechanics and computer simulations*, Molecular Physics, **80**, 1183-1193 (1993).
[2] R.A. Sack*, Pressure-dependent partition functions*, Molecular Physics, **2,** 8-22, (1959).
[3] S. Hilbert, P. Hänggi, J. Dunkel, *Thermodynamic Laws in isolated systems*, Phys. Rev. E **90**, 062116 (2014).
[4] P. Talkner and P. Hänggi, *Statistical mechanics and thermodynamics at strong coupling: Quantum and classical*, Rev. Mod. Phys. **92**, 041002 (2020).

The sensitivity of epidemic spreading to noise and long-range dispersal

T. Okada[1,2], Q. Yu[3], G. Issacchini[4,5] and O. Hallatschek[4,5]

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The COVID-19 pandemic underscored the need for accurate epidemic forecasting to predict pathogen spread, healthcare challenges, and to evaluate interventions. However, obtaining accurate forecasts is often challenging because models of rapid epidemic spread are sensitive to noise and long-range connections. Large uncertainties plague these parameters, which are not known directly and often inferred indirectly from proxy data like contact surveys and mobility. We show that the steep ramp up of genome sequencing surveillance during the pandemic can be leveraged to directly measure demographic noise and identify transmission patterns between communities. Using a hidden Markov model, we infer the fraction of infections imported by a community from others, based on how quickly allele frequencies converge between them. Analyzing SARS-CoV-2 sequencing data from England and the U.S., we reveal networks of inter-community transmission, highlighting both geographic relationships and significant long-range interactions. We show that transmission patterns can change between variant waves and analyze how the inferred plasticity and heterogeneity in inter-community transmission impacts evolutionary forecasts. This work highlights the utility of population genomic time series for illuminating epidemiological interactions.

References

[1] Okada, T., Isacchini, G., Yu, Q., and Hallatschek, O., 2024. Uncovering heterogeneous inter-community disease transmission from neutral allele frequency time series. *bioRxiv*

[2] Yu, Q., Ascensao, J.A., Okada, T., COVID-19 Genomics UK (COG-UK) Consortium, Boyd, O., Volz, E. and Hallatschek, O., 2024. Lineage frequency time series reveal elevated levels of genetic drift in SARS-CoV-2 transmission in England. *Plos Pathogens*, *20*(4), p.e1012090.

[3] Paulose J, Hallatschek O. The impact of long-range dispersal on gene surfing. Proceedings of the National Academy of Sciences. 2020 117(14):7584-93.

Evolution of Therapy Resistance in Spreading Cellular Populations

S. Aif[1,2,3], N. Appold[1,2,3], O. Hallatschek[4], J. Kayser[1,2,3]

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[3] Friedrich Alexander Universität Erlangen-Nürnberg, Erlangen, Germany
[4] University of California, Berkeley, USA

The emergence of resistant mutants in pathogenic cell populations poses a significant challenge for modern antibiotic and anti-cancer therapies. The complex spatio-temporal spreading dynamics inherent in microbial biofilms and solid tumors likely play a critical role in shaping resistance evolution and therapy response in these systems. Yet, systematic empirical study of these processes remains challenging. In this presentation, I introduce an integrated approach that combines genetically tailored microbial and cancer-cell experiments with principles from active granular matter physics and numerical modeling. This approach reveals how density-mediated collective dynamics can facilitate the emergence of resistance, thereby increasing the risk of therapy failure. I will also share recent insights into how viewing tumors as expanding active granular matter can inform the development of evolution-based adaptive therapeutic strategies.

Hydrodynamics and super-diffusive spreading of heat in one-dimension

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Hydrodynamics theory often appears to be a power tool to describe macroscopic phenomena like transport of conserved quantities. Harmonic system being an integrable system, one expects a different hydrodynamics than the usual one for a non-integrable system. In the first part, I will discuss generalised hydrodynamics of the harmonic system and ballistic transport in the context of the domain wall problem. In the second part, I will discuss how the transport becomes super-diffusive when the integrability is broken by introducing some stochastic noises. I will show how to describe super-diffusion in this case using non-local kernel operators. In the third part, I will discuss how one can identify such kernel operators from local current-current correlations measured in numerical simulations.

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Intermittent transport phenomena in active matter systems

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Active matter systems, ranging from swimming microorganisms to catalytic colloids, are characterized by transforming energy into directed motion, driving them far from equilibrium and generating a range of unusual physical phenomena. Their dynamics are subject to strong stochastic fluctuations [1] and tumbling mechanisms [2] that compete with their directed swimming motion, leading to large-scale diffusive spreading. In addition, external stimuli, complex fluid properties, and geometric confinement, omnipresent in their natural environments, can strongly modify this picture and lead to intricate intermittent dynamics. In this talk, I will discuss a theoretical framework, based on renewal equations, to analytically describe these transport processes and quantitatively characterize the dynamics of run-and-tumble bacteria and sperm cells under different environmental conditions.

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Search phenomena in immune cells

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Immune cells are often called the ‚sentinels' of the immune system, constantly searching for any kind of pathogen. During this search, immune cells spread over a given area with the task of finding objects in the most efficient way. Parameters that influence this search are migration speed, migration persistence and the correlation between the two [1]. These parameters can be modulated to diversify search strategies [2]. We have investigated how we can modify either the cellular environment or the cellular cytoskeleton (all types) to control migration and the search efficiency [3, 4].

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Distinguishing Between Lévy and Intermittent Strategies in Foraging Dynamics

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Foraging, a complex spatio-temporal behavior, is widely analyzed through stochastic models, notably Lévy walks (LWs) and intermittent search (IS). These paradigms have independently explained various observed foraging patterns, but distinguishing between them remains challenging due to similarities in trajectory characteristics. This work introduces a novel methodology combining analytical metrics and machine learning algorithms to classify eye-gaze trajectories collected during unconstrained visual foraging tasks.

Experiments with 120 participants, employing high-precision eye-tracking technology, generated a large dataset of gaze trajectories. Each participant engaged in a 180-second search for hidden visual elements within a randomized field of pixels. The recorded trajectories were analyzed using a scoring function based on the second and fourth moments of displacement data, enabling quantitative comparison between the LW and IS models.

Results indicate that the IS model, characterized by alternating ballistic and diffusive phases, better approximates 91.7% of the trajectories compared to LWs. This finding aligns with the physiological dynamics of human gaze, suggesting that IS strategies offer a more accurate framework for modeling visual foraging. The proposed method emphasizes the classification of individual trajectories rather than ensemble-level analysis, advancing our understanding of the underlying mechanisms of search behavior.

This research underscores the potential of score-based model selection frameworks for resolving ambiguities in stochastic modeling. Applications of this approach extend beyond human foraging, with implications for robotics, ecological studies, and machine vision systems.

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Proteins: An Equation of State

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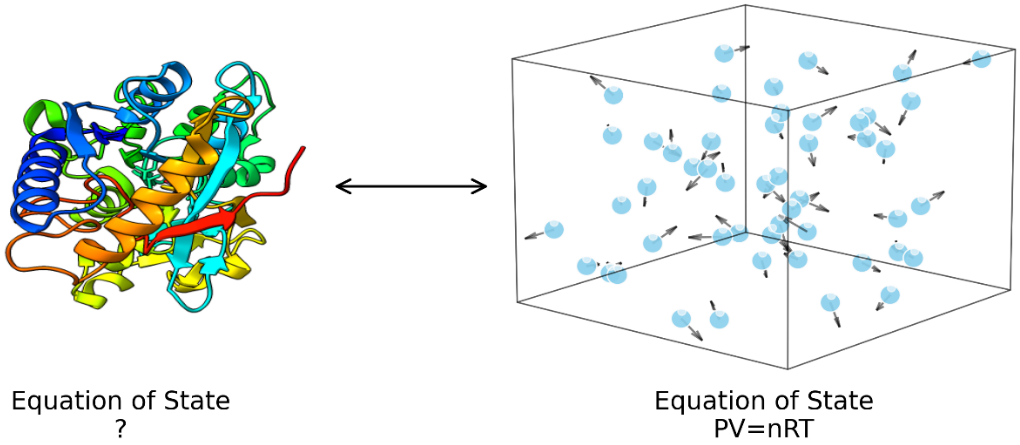

A protein's structure is intrinsically connected to its function. It exhibits stability alongside thermal fluctuations around its native folded state. These fluctuations are governed by the spectral dimension. Burioni et al. suggested that there is a correlation between the spectral dimension and the permitted size (number of amino acids) of a protein [1]. Further work examined the delicate balance between a protein's flexibility and stability [2], taking into account the fractal dimension, a measure of porousness. Since then the Protein Data Bank has expanded exponentially. We revisit these ideas and uncover new relations.

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From Physics to Health and AI with Eye-Tracking Data Analysis

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Novel search algorithms inspired by eye-gaze trajectories admit a list of potential applications in autonomous robotic search where the search time is critical such as target detection in surveillance applications and visual scan for self-driving cars. Mathematical research tends to forego that the eyes are intrinsically linked with the cognitive process. Here, eye movements are often treated as a simple way to forage for visual information. That is, however, a crude simplification: human scan-paths reflect more than just a strategy to forage for visual information and they seem to be more complex than the aforementioned intermittent processes and other searching strategies such as LÃ©vy flights. Both these mathematical processes are seemingly universal in explaining the foraging behaviour in processes as diverse as the hunting movement of albatrosses and sharks, the movement of swimming bacteria or the exploration of the Walt Disney Resort by children. Yet, paradoxically, the debate is still ongoing what its general form actually is. Here we discuss the hypothesis that some of the added complexity of gaze trajectories, when compared to Levy flights or intermittent processes, are designed to optimize the search for visual information. Additionally, we will show some cases where such optimal tynning enables also interesting applications in health diagnosis.

Exploring the adjacent possible: play, anticipation, surprise

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Abstract

Novel experiences frequently occur in our daily lives. We meet new people, learn and use new words, listen to new songs, watch new movies, and adopt new technologies. These unique experiences can happen by chance but are often triggered by previous experiences, highlighting a compelling correlation between their occurrences. Historically, the concept of "new" has presented challenges to humanity. What is considered new often defies our natural tendency to predict and control future events. Despite this, we base many of our decisions on our expectations about the future. From this perspective, understanding how novelties emerge and how humans anticipate their occurrence is essential for progress in all areas of human activity. The common intuition that one new thing often leads to another is mathematically captured by the concept of the "adjacent possible." [1] This refers to the collection of ideas, linguistic structures, concepts, molecules, genomes, technological artefacts, etc., that are one step away from what currently exists. Innovations can arise from incremental modifications and the recombination of existing materials. In this talk, I will present a mathematical framework [2, 3, 4] that describes the expansion of the adjacent possible. This framework's predictions are borne out in several data sets drawn from social and technological systems.

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Routing of ticket control teams in urban transportation networks as an optimization problem: A quantum annealing approach

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Abstract

Effective ticket control is essential for maintaining sustainability of urban public transportation systems operating on the proof-of-payment principle. Beyond simply maximizing revenue, the objectives of the control include such factors as 'fairness' (in covering different urban areas) and high mobility of the teams across various transit lines and stations. These factors make the task of team scheduling and routing a complex optimization problem. We try to capture this complexity with two models. The first model follows the idea of the Exponential-weight algorithm for Exploration and Exploitation (EXP3) used to classify stations by fare evasion risk. The model also includes the fairness factor as part of the cost function. The second model frames the deployment task as a particular case of vehicle routing problems with time windows, ensuring that inspections are conducted within specified time constraints. To solve the model problems, we first transpile them into the Quadratic Unconstrained Binary Optimization framework and then use a cloud-accessible *D-Wave* quantum annealer (QA) to find solutions. We used both synthetic data sets and data collected from the Oslo metropolitan area to test the models and benchmark the performance of QA against conventional solvers. Our results suggest that QAs can be effective on large scales and can outperform traditional solvers (including Gurobi) in both solution optimality and computation time.

The role of higher-order hierarchical structures in complex spreading processes

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Contagion processes are often modelled as *simple contagion*, by involving two individuals at a time, and *networks* have been widely used to describe the binary interactions which constitute the substrate for these spreading phenomena. However, pairwise interactions are often not enough to describe social contagion, such as opinion formation, where group mechanisms of reinforcement and influence are active. Individuals usually interact in groups, requiring to go beyond the network representation and consider *complex contagion* [1].

Hypergraphs represent a powerful framework to describe group interactions: in this higher-order generalization of networks, nodes interact in hyperedges of arbitrary size. Higher-order interactions induce novel phenomena, hence it is crucial to unveil the impact of the hypergraph topology on complex contagions. Here we propose a procedure to decompose a hypergraph into *hyper-cores* [2], generating a hierarchy of sub-hypergraphs of increasing connectivity, composed of interactions of increasing size. We identify non-trivial mesoscopic structures, intrinsically higher-order, and develop a new node centrality measure, the *hypercoreness*.

We apply this decomposition to empirical hypergraphs, and we show the crucial role of this hierarchical structure in different spreading processes with higher-order mechanisms [2]. The cores sustain and drive higher-order contagion processes, since the spreading tend to localize on hyper-cores of high connectivity and high interaction order; if the seeding of the spreading process is within these cores, the total outbreak size is maximized. Moreover, in the emergence of social conventions, few committed individuals with high hypercoreness can rapidly overturn a majority convention, more efficiently than if chosen according to simple pairwise centralities.

Our work opens multiple research directions from understanding higher-order spreading processes on hypergraphs to designing targeted interventions to favour or limit the spreading when complex contagion mechanisms are active.

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Non-Gaussianity and varying scaling exponents in long-range dependent motion

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Stochastic processes with long-range dependent correlations naturally emerge in many systems when degrees of freedom are integrated out, apart from the dynamic of the (tracer) particle of interest. In non-equilibrium situations, the resulting overdamped dynamics often corresponds to fractional Brownian motion (FBM).

In disordered systems the observed displacement probability density is often non-Gaussian, and FBM-type processes display scaling exponents varying in time or space. This talk introduces diffusion models with stochastically [1, 2] and deterministically [3, 4] varying diffusion coefficients and scalingi exponents. Apart from the more traditional Mandelbrot-van Ness formulation of FBM, Levy's non-equilibrium approach via a fractional integral will also be discussed. Various applications to experimental data will be introduced.

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Intermittent active motion for enhanced spatial exploration

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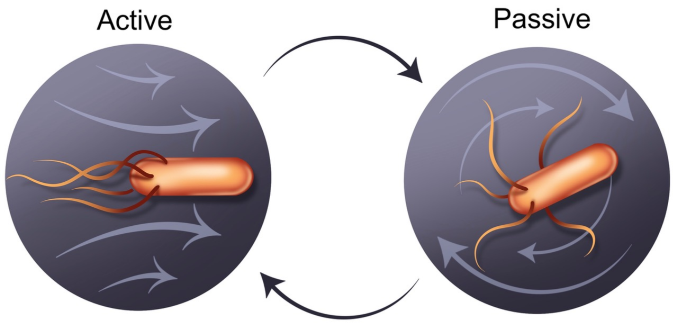

When does stopping make you go faster? Intermittent dynamics is a ubiquitous phenomenon in nature, with examples including nano-tracers in heterogeneous media, the motility patterns of cells, and foraging strategies observed in macroscopic living animals. Recently, much attention has been given to intermittent active motion, where self-propelled particles stochastically switches between a mobile and an immobile phase. Here, we present recent results showcasing the conditions under which intermittent motion serves as a beneficial strategy of motion. In particular, we discuss intermittent active processes that switch between mobile and immobile phases with and without memory of past phases, with active chiral particles serving as our main case study. We identify phase diagrams where enhancement of effective diffusion can be observed, and provide physical intuition for the results [1]. Connections will be made to more general composite dynamical processes and stochastic resetting processes [2,3].

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Heat transport in classical systems: a review of open problems

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Almost 30 years ago, it was found that energy propagation in chains of nonlinear oscillators may be anomalous, i.e. it may not obey Fourier law. Over the years, experiments have confirmed the preliminary results, while numerical simulations unveiled a many-sided scenario.
Fluctuating hydrodynamics suggests the existence of different universality classes, depending on whether linear momentum is conserved and on the presence of symmetries: for instance, in the broadest class (in the presence of momentum conservation) the expected growth rate (with the system length) of the heat conductivity is 1/3.
Although this theory accommodates many results, a few remarkable exceptions suggest the need of a more convincing explanation: for instance, very detailed numerical simulations show that the growth rate in some symmetric potentials is close to 2/5, rather than the expected ½.
Furthermore, there is no stochastic model which reproduces the behavior expected for the broadest universality class.
I'll go through all the results, discussing potential explanations (including the presence of finite-size corrections) and suggesting further directions to be examined.

Sokoban: a model for percolation with obstacle-pushing

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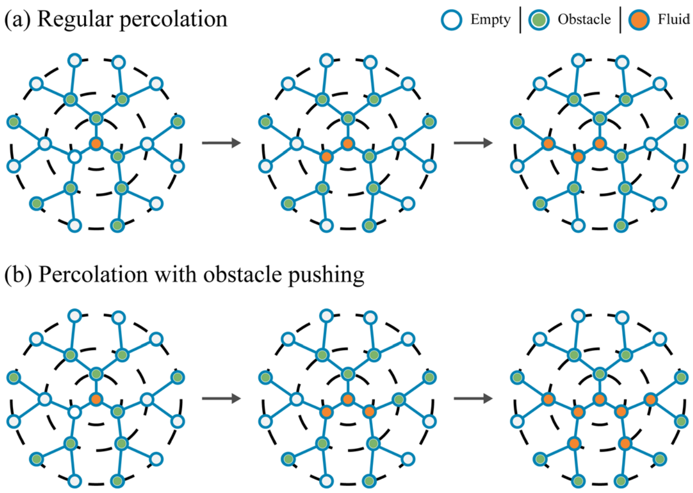
Alfréd Rényi once humorously remarked that a mathematician functions as a contraption designed to convert coffee into theorems. Though the precise ritual of brewing one's morning cup may vary, the essence lies in the process of extraction. This requires water to find its way through the ground coffee beans and into the cup. However, can water do so effectively? And is there always a path that will allow them to percolate from top to bottom? Percolation theory emerged as an attempt to tackle this and similar questions mathematically. It can thus be ironically described as a concerted effort to convert coffee into theorems about coffee.

Observe an espresso puck before (left) and after (right) the extraction process. As hot pressurized water is pushed through the puck, it does not leave the original arrangements of coffee grains intact. Rather, it paves its way through the grains, displacing them from their original positions (see the holes formed in the used puck on the right). However, canonical models for percolation assume that obstacles (coffee grains) are static, completely ignoring any interaction between them and the percolating liquid.



In this talk, I will introduce *Sokoban percolation*, a model that challenges the conventional assumptions of percolation theory by allowing for weak and localized obstacle-pushing (see figure). By exploring how such interactions affect transport across different network topologies, e.g., the Bethe lattice and the 2D lattice, I will show that they have a profound effect that cannot be neglected when coming to understand spreading phenomena in disordered media.

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Homogenization problems for generalized Langevin equation: The bath always wins

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Generalized Langevin equations may describe a wealth of sub-, normal and super-diffusive regimes. More than a decade ago, Goychuk reported on a universal behavior of subdiffusive motion in a one-dimensional bounded periodic potential [1], where numerical findings show that the behavior in the potential, under homogenization, is the same as in its absence. Thus, the behavior in subdiffusive domain is quite peculiar, since it shows no sensitivity to external influences ("the bath always wins"), as long as the external potential is bounded and shows no long-range correlations.

Here, we report on the results of simulations of subdiffusion in two different two-dimensional situations with *unbounded* potentials modelled via non-holonomic constraints. One of them corresponds to a periodic array of solid obstacles with different packing fractions [2]. Also in this case the subdiffusive behavior at long times is not influenced by the presence of solid scatterers: Their presence influences the behavior at intermediate times only. Another situation corresponds to the motion of tracer particles in channels of different shapes and of indefinite length in the x direction [3]. The two situations considered in [3] correspond to channels of varying width and to channels with meandering midline. The subdiffusion in the x direction is not affected by constraints put by the channel. This is especially astonishing for meandering channels whose centerline might be quite long. The same behavior is seen in a holonomic model of a bead on meandering wires.

A discussion of a specific model of the bath, namely of a Rouse polymer chain attached to the tracer bead on a meandering wire, makes the situation much less mysterious. On the one hand, it shows that the same independence arises in the case when subdiffuion is only an intermediate asymptotic regime of the behavior, and is succeeded by a normally diffusive terminal behavior. On the other hand, considering corresponding limiting cases shows how this independence emerges on the large time- and space-scales provided the constraints on the tracers' motion do not affect the bath. The situation changes drastically when the constraints are applied to the bath's particles' motion.

The results are discussed as having possible relations to the emerging problem of interpretation of experiments on trajectories of tracers spreading in the neuronal axons and in the brain's extracellular space.

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Subordination processes for non-Gaussian diffusion

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In this talk I will introduce the general mechanism leading to non-Gaussian diffusion in subordination processes, highlighting the "tail" and "central" effects. Two dynamical regimes, characterised by different scaling properties of the PDF for the subordinator, will be discussed. After presenting various subordination models (diffusing diffusivity,

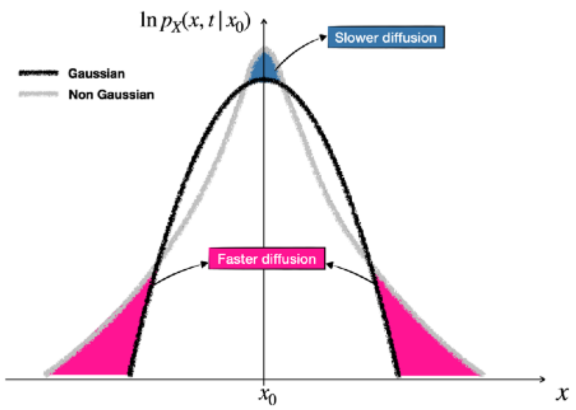

Figure 1: Comparison between Gaussian and non-Gaussian probability density functions for subordination processes. The two PDFs share the same mean and standard deviation but the non-Gaussian one has an excess probability both in the tails and in the center part.

polymers in the grand canonical ensemble, continuous-time random walks), I will address the following question: is non-Gaussian targeting more efficient than Gaussian? In terms of customary mean first-passage time, I will show that Gaussian searches are more effective than non-Gaussian ones. Non-Gaussianity, instead, becomes highly more efficient in applications where only a small fraction of tracers is required to reach the target, introducing drastic corrections to the known Gaussian behaviour. Finally, I will provide an overview of ongoing work & future outlook.

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The emergence of cooperation from shared goals in the governance of common-pool resources

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Sustainable use of common-pool resources is a major environmental governance challenge because of possible overexploitation. Communities devise self-governing institutions that avoid overuse and attain long-term benefits of cooperation. It is still unclear, however, what conditions allow cooperation to emerge, leading to greater long-term benefits. Until recently, studies of the sustainable governance of common-pool resources have overlooked feedback between user decisions and resource dynamics and failed to test the ability of shared goals to actually induce cooperation. Here we develop an online game to perform a set of experiments in which users of the same common-pool resource decide on their individual harvesting rates, which in turn are influenced by the resource dynamics. In this talk I will show that if users share common goals, a high level of self-organized cooperation emerges, leading to long-term resource sustainability. Otherwise, selfish/ individualistic behaviours lead to resource depletion. To explain these results, we develop a model of resource-decision dynamics based on optimal control theory and show how it is able to reproduce empirical results. We find that players self-organize and engage in collective action conducive to sustainable governance of common-pool resources by trade-off strategies that balance individual and collective payoff as well as short-term and long-term rewards.

Rereference: *Tu et al., Nature Sustainability 6 (2), 139-147*

Bacterial spreading in complex environments, from individuals to populations

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Many bacterial species employ biased random walk strategies to navigate chemical concentration fields in a process termed “chemotaxis” that results in an average drift up a chemical gradient. The type, statistics, and chemotactic performance of the biased random walk depend both on properties of the bacterium and of the environment. I will discuss our work [1] investigating how, in nature, bacterial properties may be optimized for specific environments to maximize chemotactic performance.
At the population-level, the underlying details of the individuals’ random walks can typically be absorbed into effective parameters such as drift and diffusivity. Chemotaxis and growth create feedback between bacterial population densities and chemical concentration fields and can give rise to collective chemotactic population spreading. The overall population growth depends on both the chemotactic spreading rate and the individual growth rate, yet in nature these two parameters are typically subject to a tradeoff due to resource limitation. I will discuss our work [2] on how such a tradeoff can enable the coexistence of two species in spatial competition.

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Dynamic Perturbation Spreading in Networks

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The spreading of initially localized perturbations across networks impacts the functionality of a wide range of systems, from social to biological networks, where ideas, nutrients or diseases spread, and to our infrastructure networks such as power grids that supply us with electricity. Despite its ubiquity, there is currently no general theory of dynamic spreading on networks, in part because it constitutes a *transient* phenomenon emerging in driven multi-dimensional nonlinear dynamical systems.

Here, we present two complementary approaches to make progress. First, even for linear networked systems it is generally impossible to analytically determine time and amplitude of the maximal response of a unit to a perturbation impinging from some other unit. We propose to extract approximate peak times and amplitudes from effective expectation values used to characterize the typical time and magnitude of the response of a unit by interpreting the system's deterministic response as a probability distribution over time. We derive analytic estimators for the peak response based on these expectation values. Further analysis suggests that these estimators become exact in the limit of weak coupling.

Second, we disentangle universal from system-specific features of the transient spreading dynamics of networks driven by fluctuating signals. We first analytically identify a purely topological factor encoding the structure and strengths of network interactions, and second, numerically estimate a master function characterizing the universal scaling of the perturbation arrival times across topologically different networks. The proposed approach thereby provides intuitive insights into complex propagation patterns as well as accurate predictions for the perturbation arrival times.

We illustrate application to models of power grids and highlight topical questions for future research.

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Big jump principle in physical modelling.

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The big jump principle has been rigorously established for the sum of independent and identically distributed random variables extracted from a fat tailed distribution [1]. It states that in the distribution that describe the sum the rare events are determined by a single random variable i.e. the largest summand. In practice, it means that the mechanism leading to rare events is not caused by a set of many small deviations all in the same direction, but one jump, the biggest of the lot, fully describe the rare large fluctuation. We extend the big jump principle beyond the case of independent random variables [2]. In this perspective we evaluate the rare events in a wide class of generalized Lévy walks [3], in scattering processes on heterogeneous structures and in the stochastic differential equations. Moreover the principle has been applied not only in the study of the tails of the distribution of the sum but also in evaluating rare events in the exit times [4] and in the extreme value statistic [5]. We argue that the generalized big jump principle can serve as a tool for estimating the risk of rare events in many complex processes featuring heavy tailed distributions.

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Abstracts of Posters

(in alphabetical order)

Likelihood-based inference for heterogeneous motile particle ensembles

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The inherent complexity of biological agents often leads to motility behavior that appears to have random components. Robust stochastic inference methods are therefore required to understand and predict the motion patterns from time discrete trajectory data provided by experiments. In many cases second-order Langevin models are needed to adequately capture the motility. Additionally, population heterogeneity needs to be taken into account when analyzing data from multiple individual organisms. We present a maximum likelihood approach to infer dynamical, stochastic models and, simultaneously, estimate the heterogeneity in a population of motile active particles from discretely sampled, stochastic trajectories. To this end we propose a new method to approximate the likelihood for nonlinear second order Langevin models. We demonstrate that the maximum likelihood ansatz outperforms alternative approaches for heterogeneity estimation, especially for short trajectories, while also providing a measure of uncertainty for the estimates. We apply this approach to uncover time-dependent heterogeneity in an experimental cell-cargo system.

Mechanical Modeling of Proliferation Dynamics in Cell Collectives

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Cell collectives play a crucial role in numerous biological processes, such as biofilm formation, tissue development, and tumor growth [1]. However, it remains unclear to which proliferation dynamics can be captured purely with mechanical descriptions. This work establishes a bridge between microscopic dynamics and macroscopic mechanical frameworks, enabling the characterization of collective properties such as pressure, velocity, and the emergence of mechanical instabilities. By integrating these approaches, the framework also aims to explore gene surfing phenomena, highlighting the role of microscopic fluctuations in shaping competitive dynamics.

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Inertial active matter governed by Coulomb friction

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Coulomb, or dry friction, is a common phenomenon that can be encountered in various systems, such as granular matter or Brownian motors. The Coulomb friction force resists the motion and, unlike the friction in wet systems, is almost independent of the relative velocity. We show that this characteristic feature of Coulomb friction leads to emergence of dynamical states when subjected to active, or self-propelled motion [1]. At low activity levels, the dynamics resembles Brownian motion, while at higher activity, a dynamic Stop & Go regime emerges, marked by continuous switching between diffusion and accelerated motion. At even greater activity levels, a super-mobile regime arises, characterized by fully accelerated motion and an anomalous scaling of the diffusion coefficient with activity. These phenomena are absent in systems dominated by velocity-dependent Stokes viscous forces typical for active swimmers, but are fundamental for dry active objects. Near the transition between the Stop & Go and super-mobile regimes, we reveal a novel activity-induced phase separation in collective behavior [2]. Our theoretical findings have been also demonstrated in experiments, where vibrobots on a horizontal surface are activated by vertical oscillations generated using an electromagnetic shaker.

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Influence of Stochastic Parameters in Spreading Phenomena

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The influence of stochastic parameters on spreading dynamics has profound implications for understanding complex systems. In this work, we investigate two paradigmatic models of spreading phenomena. First, we introduce a doubly stochastic continuous time random walk (DSCTRW), where the jump rate evolves as a stochastic process. This model captures key features of heterogeneous environments, revealing transitions between short- and long-time regimes while maintaining mathematical tractability. Second, we analyze diffusion with doubly stochastic resetting, where the resetting rate fluctuates over time. Our findings reveal a rich interplay between short-time superstatistical behavior and long-time steady states governed by an effective resetting rate.

Both models demonstrate how stochasticity in key parameters modifies spreading behaviors, leading to non-trivial dynamics and first-passage properties. These results provide a unified framework for exploring spreading processes across a wide range of contexts, from transport in disordered media to biological systems.

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Rare Events and Single Big Jump Effects in Ornstein-Uhlenbeck Processes

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Even in a simple stochastic process, the study of the full distribution of complex observables can be a difficult task. This is the case, for example, of a much-studied process such as the Ornstein-Uhlenbeck process where, recently, anomalous dynamical scaling of large deviations for complex observables has been highlighted [1, 2]. Using the mapping of a continuous stochastic process to a continuous time random walk via a discrete renewal process by means of the "excursions technique" [3], we introduce a comprehensive formalism that enables the calculation of the complete distribution of the time-integrated observable $A = \int_0^T v^n(t)dt$, where n is a positive integer and $v(t)$ is the random velocity of a particle following Ornstein-Uhlenbeck dynamics. In particular, we show that the case of anomalous scaling of large deviations, originally associated to the presence of an instantonic solution in the weak noise regime of a path integral approach, is produced by a so called "big jump effect" [4], in which the contribution to rare events is dominated by a single process. By treating both the bulk of the distribution and the rare events with the same approach, we are also able to identify the critical point at which the dynamical transition between these two regimes occurs [5]. Our approach, which is quite general for continuous stochastic processes, allows to associate a physical meaning to the anomalous scaling of large deviations.

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Modeling Eye Gaze Trajectories Using GANs and Markov Models

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Accurate modeling of eye gaze dynamics is essential for advancing human-computer interaction, neurological diagnostics, and cognitive research. Eye gaze trajectories can be viewed as a form of spreading phenomenon, where the movement dynamics are influenced by internal cognitive states, memory constraints, and perceptual processes. Traditional generative models like Markov models struggle to capture the intricate temporal dependencies and distributional nuances inherent in these trajectories, limiting their ability to model such complex, adaptive behaviors. This study introduces a Generative Adversarial Network (GAN)[2] framework incorporating Long Short-Term Memory (LSTM) and Convolutional Neural Network (CNN) architectures as generators and discriminators to produce high-fidelity synthetic eye gaze velocity trajectories. We evaluate four GAN configurations—CNN-CNN, LSTM-CNN, CNN-LSTM, and LSTM-LSTM—trained under two conditions: with adversarial loss and a weighted combination of adversarial and spectral losses. Our findings show that the LSTM-CNN architecture, trained with spectral regularization,[3] closely aligns with real data distributions, effectively capturing both the distribution tails and intricate temporal dependencies that reflect the spreading dynamics of gaze movements. The inclusion of spectral loss significantly enhances the GAN's capacity to replicate the frequency characteristics of eye gaze trajectories. By framing eye gaze trajectories as a spreading phenomenon, our approach highlights how internal cognitive dynamics shape movement patterns, drawing parallels to how agents in other systems interact with and adapt to their environments.
Comparative analysis with a Hidden Markov Model (HMM)[1,4] optimized to four hidden states underscores the superiority of the LSTM-CNN GAN. While the HMM-generated data diverges significantly from real data in terms of mean, standard deviation, skewness, and kurtosis, the LSTM-CNN model exhibits a remarkable ability to match these statistics, affirming its effectiveness in capturing the complex temporal and distributional properties of eye gaze dynamics. These results position the spectrally regularized LSTM-CNN GAN as a powerful tool for modeling synthetic eye gaze velocity data with high fidelity. By bridging cognitive science and the physics of spreading phenomena, this work opens new avenues for understanding and simulating systems where internal states drive adaptive, dynamic behaviors. Such insights hold promise for applications in simulation environments, advanced eye-tracking technologies, and human-computer interaction, ultimately enabling more responsive and naturalistic interfaces.

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Propagators and persistence exponents of self-interacting random walks

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(Dated: December 2, 2024)

The persistence exponent, which characterises the long-time decay of the survival probability of stochastic processes in the presence of an absorbing target, plays a key role in quantifying the dynamics of fluctuating systems. Determining this exponent for non-Markovian processes is known to be a difficult task, and exact results remain scarce despite sustained efforts. We consider the fundamental class of self-interacting random walks (SIRWs), which display long-range memory effects that result from the interaction of the random walker at time t with the territory already visited at earlier times $t' < t$. We compute exactly the persistence exponent for all physically relevant SIRWs, as well as their propagator. As a byproduct, we also determine the splitting probability of these processes. Besides their intrinsic theoretical interest, these results provide a quantitative characterization of the exploration process of SIRWs, which are involved in fields as diverse as foraging theory, cell biology, and machine learning.

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Survival probability for a run-and-tumble particle with an arbitrary flight time distribution

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Run-and-tumble particle (RTP) is a random walk model often used to describe the behavior of active matter. This model appears in various spreading phenomena, ranging from active gels and self-catalytic colloids to living cells and bird motility. The RTP usually describes active particle motion with two alternating stages. First, the particle moves ballistically in a specific direction at a constant speed for a certain flight time. After this period, the particle tumbles, meaning it randomly selects a new direction uniformly. Then, it begins another ballistic run in the chosen direction, again moving at a constant speed for a random duration. This process continues repeatedly.

Commonly, flight times are independently distributed exponential random variables; thus, particle tumblings occur at a constant rate. In Ref. [1], Mori, Le Doussal, Majumdar, and Schehr investigated the RTP in the arbitrary d dimension and exactly calculated the survival probability that the x-component of the position of the RTP starting from the origin remains positive up to time t. Utilizing the Sparre Andersen theorem, they demonstrated that when tumbling occurs at a constant rate, this probability is universal, i.e., independent of the dimension d for any time t. Additionally, the authors showed that this universal result applies to a broader range of RTP models where the particle velocity after each tumbling is random, and this velocity for every ballistic event is drawn from an arbitrary probability distribution.

In this work, we generalize the result obtained in the paper [1] by extending their problem to the case when flight times do not have only an exponential but an arbitrary probability density function (thus, particle tumblings occur at a non-constant rate). We derive the closed-form expression of the survival probability in the Laplace space. In general, it shows that the universality of the survival probability is broken. Namely, this function depends on the dimension d and the velocity distribution. We find exact inversions of this expression in several partial cases and calculate asymptotic formulas for the survival probability at small and large times in a general case. Also, we verify analytic results by numerical simulation.

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Pedestrian fluxes in confined geometric networks: entropic measures and robustness of accessibility in a university campus

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When discussing urban life, pedestrian accessibility to all main services is crucial for fostering social interactions, promoting healthy lifestyles, and reducing pollution. This is especially relevant in coherent urban agglomerations like university campuses, which feature a high concentration of streets and social facilities. Using Wi-Fi data, we study pedestrian movements within a confined geometric network representing the pathways on a university campus. We estimate the level of crowding in each arc of the network and identify pedestrian flows along all possible paths, measuring the entropy and robustness of the network. In particular, we calculate the information gain achieved through the use of Wi-Fi data and we assess how pedestrian traffic redistributes within the network after the removal of individual arcs. Our results can be used to facilitate the investigation of the current state of walkability across the university campus while also testing a set of methods for analyzing urban complex networks, potentially allowing us to pinpoint areas in urgent need of road maintenance and enhancement.

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Hydrodynamic Transport and Clustering in Cellular Aggregates Driven by Contractile Forces

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The large-scale collective behavior of biological systems is often characterized by macroscopic transport phenomena that emerge from non-equilibrium microscopic interactions among individual constituents. A notable example is the clustering and associated slowdown of transport observed in colonies of *Neisseria gonorrhoeae* bacteria, driven by active contractile forces mediated by pili. In this study, we analytically derive the fluctuating hydrodynamics from the microscopic dynamics of a 2D model system representing an *N. gonorrhoeae* bacterial colony. The hydrodynamic current of the cells is governed by two macroscopic transport coefficients: bulk diffusivity and conductivity, both of which depend on cell density and other microscopic parameters. Strikingly, simulation results strongly align with the analytical predictions, confirming the transport slowdown during colony formation. This work offers valuable insights and experimental approaches for studying hydrodynamic transport in cellular aggregates driven by contractile forces, such as tumor spheroids and neuronal organoids.

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Dynamics of intermittently self-propelled particles

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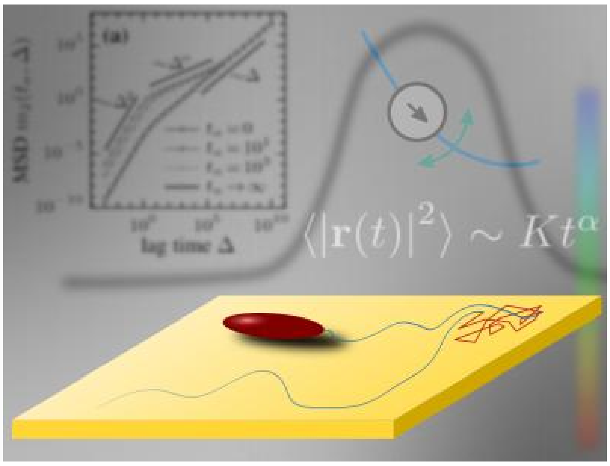
Several experiments over the past decade have demonstrated the motion of active particles in various complex and disordered environments. Motivated by these findings, we propose a dynamical model of a self-propelled particle that recurrently switches between two phases of motion: an active run state and a passive turn state, with durations drawn from arbitrary waiting-time distributions. We derive exact expressions for key transport characteristics, such as mean-squared displacement and the long-term diffusion coefficient, which can be readily validated experimentally. Furthermore, we explore different limiting cases of our model that correspond to well-known transport processes, including the run-and-tumble motion of bacteria, hop-and-trap dynamics, continuous-time random walks, Lévy walks, and others. Finally, we show how we can apply this model to understand the motility characteristics of swimming bacteria in porous gels.



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Routing of ticket control teams in an urban transportation network as an optimization problem: A quantum annealing approach

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Abstract

Effective ticket control is essential for maintaining sustainability of urban public transportation systems operating on the proof-of-payment principle. Beyond simply maximizing revenue, the objectives of the control include such factors as 'fairness' (in covering different urban areas) and high mobility of the teams across various transit lines and stations. These factors make the task of team scheduling and routing a complex optimization problem. We try to capture this complexity with two models. The first model follows the idea of the Exponential-weight algorithm for Exploration and Exploitation used to classify stations by fare evasion risk. The model also includes the fairness factor as a part of the cost function. The second model frames the deployment task as a particular case of vehicle routing problem with time windows, ensuring that inspections are conducted within specified time constraints. To solve the model problems, we first transpile them into the Quadratic Unconstrained Binary Optimization framework and then use a cloud-accessible *D-Wave* quantum annealer (QA) to find solutions. We use both synthetic datasets and data collected from the Oslo metropolitan area to test the models and benchmark the performance of the QA against conventional solvers. Our results suggest that QAs can be highly effective at large scales and can outperform traditional solvers (including Gurobi) in both solution optimality and computation time.

Striking universalities in dynamical observables

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The study of chaotic systems, where rare events play a pivotal role, is essential for understanding complex dynamics due to their sensitivity to initial conditions. Recently [1, 2, 3], tools from large deviation theory have been applied in the study of chaotic systems, describing the probabilities of dynamical observables through rate functions. Large deviation theory allows us to go beyond the traditional central limit theorem, describing the statistics of rare events in physical systems. Here, we demonstrate that certain dynamical observables, $A_N = \sum_{n=1}^{N} g(x_n)$, defined along a chaotic trajectory $\{x_1, x_2, \ldots, x_N\}$, exhibit a remarkable statistical universality: even when constructed with distinct functions $g(x)$, some observables are described by the same rate function. We provide a physical interpretation for this striking universality. Furthermore, we show that for a certain class of observables, the distribution of A_N becomes independent of N in the large-N limit.

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A stochastic model for a competition of two microbial species with public-good production controlled by quorum-sensing

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We propose a model that describes the competition dynamics of two microbial species. One performs a collaborative collective behavior to produce public good (PG) that benefits not only their existence but also the existence of the other species, the cheaters. We introduce quorum sensing (QS) on the public-good producers as a communication mechanism that controls the production of PG. The model aims to unveil the conditions under which the public-good producers persist and overcome cheating and the conditions that drive them to extinction. The dynamics are performed on a square lattice where the total number of individuals is conserved. The interactions are governed by stochastic rules analog to the Majority Vote model. Evolutionary game theory is applied to define the reproduction mechanisms. Our results are supported by Monte Carlo simulations and a simple mean-field approximation of the model is proposed.

Dynamical Spreading Under Power Law Potential

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In this work, we examine the dynamic spreading of a dense overdamped suspension of particles under power law repulsive potentials, often called Riesz gases. That is, potentials that decay with distance as $\frac{1}{r^k}$ where $k \in (-2, \infty]$. Depending on the value of k relative to the system's spatial dimension D, the potentials are categorized as short-ranged for $k > D$ and long-ranged when $k \leq D$. Such systems naturally occur in contexts involving particle suspensions, granular media, and charged systems, where interactions can be influenced by physical fields that decrease over distance.

Our analytical findings reveal that the particles spread in a self-similar form, with the radius growing with time as $t^{\frac{1}{k+2}}$. The theoretical predictions derived for a general dimension D, are verified by numerical simulations involving thousands of particles in free space, in both one and two dimensions. Furthermore, the simulations not only confirm our analytical results but also reveal a rich diversity of behaviors depending on the value of k. We demonstrate that the density profiles differ significantly depending on whether k is larger than, smaller than, or equal to D-2, where D is the dimension. For $k > D$-2 the density is centered in the middle and we also notice a Wigner lattice emerging as a result of the repulsive interactions, for $k = D$-2, density is uniform and for $k < D$-2, density is centered at the edges. This new classification indicates that the long/short-range classification is insufficient for predicting the density profile of the suspension. When $k <$ D-2, we observed an interesting phenomenon when two or more suspensions are placed near each other: a particle-free zone is formed where the two populations meet, resembling structures of bubbles.

By bridging analytical theory, numerical simulations, and preliminary experimental observations, this work provides a comprehensive understanding of the spreading dynamics in overdamped Riesz gases. Our findings enrich the fundamental knowledge of particle systems with power-law interactions, and also offer insights into a wide range of applications, from material science to biological systems, where such interactions play a major role.

First-passage time of a Brownian searcher with stochastic resetting to random positions

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We study the effect of a resetting point randomly distributed around the origin on the mean first-passage time of a Brownian searcher moving in one dimension. We compare the search efficiency with that corresponding to reset to the origin and find that the mean first-passage time of the latter can be larger or smaller than the distributed case, depending on whether the resetting points are symmetrically or asymmetrically distributed. In particular, we prove the existence of an optimal reset rate that minimizes the mean first-passage time for distributed resetting to a finite interval if the target is located outside this interval. When the target position belongs to the resetting interval or it is infinite then no optimal reset rate exists, but there is an optimal resetting interval width or resetting characteristic scale which minimizes the mean first-passage time. We also show that the first-passage density averaged over the resetting points depends on its first moment only. As a consequence, there is an equivalent point such that the first-passage problem with resetting to that point is statistically equivalent to the case of distributed resetting. We end our study by analyzing the fluctuations of the first-passage times for these cases. All our analytical results are verified through numerical simulations.

Laplace's first law of errors applied to diffusive motion

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ABSTRACT

In biological, glassy, and active systems, various tracers exhibit Laplace-like, i.e., exponential, spreading of the diffusing packet of particles. The limitations of the central limit theorem in fully capturing the behaviors of such diffusive processes, especially in the tails, have been studied using the continuous time random walk model. For cases when the jump length distribution is super-exponential, e.g., a Gaussian, we use large deviations theory and relate it to the appearance of exponential tails. When the jump length distribution is sub-exponential the packet of spreading particles is described by the big jump principle. We demonstrate the applicability of our approach for finite time, indicating that rare events and the asymptotics of the large deviations rate function can be sampled for large length scales within a reasonably short measurement time.

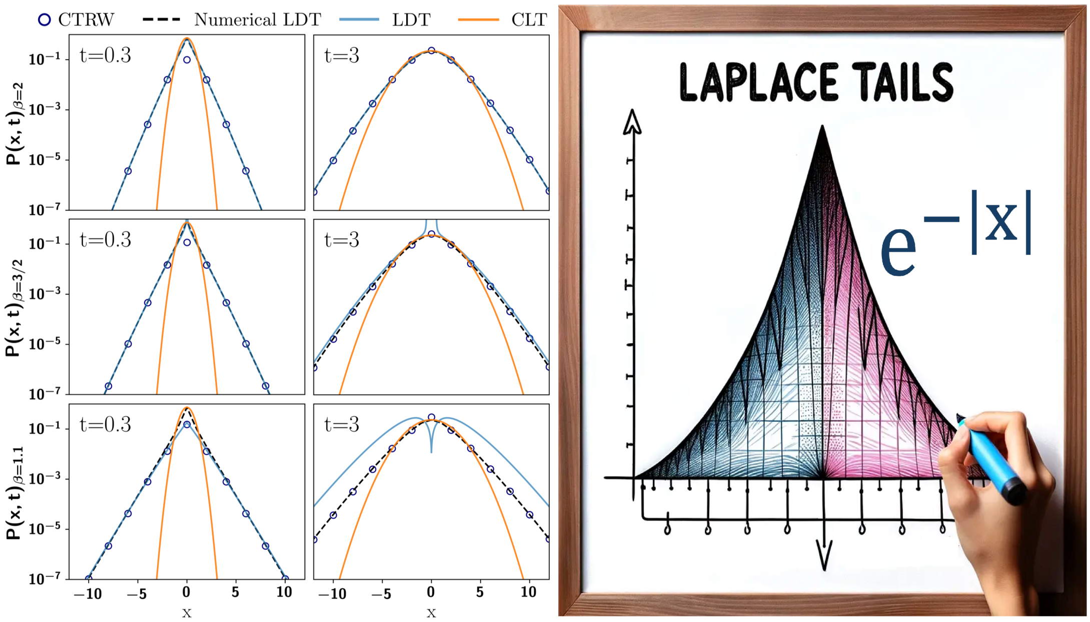

FIGURE 1. On the left, we present the key results of our theory, highlighting the universality of the exponential-like (Laplace) tails of the probability density function. The circles represent exact numerical results, while CLT refers to the central limit theorem with a Gaussian distribution, and LDT denotes our proposed analytical theory. On the right, a graphical illustration visualizes the exponential tails.

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Universal linear response of the mean first-passage time

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First-passage processes are pervasive across numerous scientific fields, yet a general framework for understanding their response to external perturbations remains elusive. While the fluctuation-dissipation theorem offers a complete linear response theory for systems in steady-state, it is not applicable to transient first-passage processes. We address this challenge by focusing on rare, rather than weak, perturbations. Surprisingly, we discover that the linear response of the mean first-passage time (MFPT) to such perturbations is universal. It depends solely on the first two moments of the unperturbed first-passage time and the mean completion time following perturbation activation, without requiring any assumptions about the underlying system's dynamics. To demonstrate the utility of our findings, we analyze the MFPT response of drift-diffusion processes in two scenarios: (i) stochastic resetting with information feedback, and (ii) an abrupt transition from a linear to a logarithmic potential. Remarkably, our approach bypasses the need for explicit problem-solving, allowing us to unravel and explain the highly non-trivial response phase space of these systems. Our results simplify the analysis of complex systems, offering a powerful tool for predicting the impact of perturbations on first-passage processes across various scenarios and research fields.

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Hybrid Models for Large Scale Infection Spread Simulations

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Since the SARS-CoV-19 outbreak, various strategies for modeling infection spread and counter-measures have been suggested. Many of the realistic models are based on so-called agent-based models (ABMs). The main advantage of ABMs is that they naturally allow the incorporation of effects like counter-measures, vaccines, and virus mutations. However, ABMs are computationally expensive, especially for stochastic ABMs that require numerous simulations and large agent numbers. Thus, ABMs are not very well suited for modeling very large regions, such as Germany. This project continues and expands upon our prior research, where we successfully laid the groundwork for modeling and simulating infection spreading in the context of the SARS-CoV-19 pandemic. This includes building and parametrizing ABMs with more than 1 million agents for Berlin and Cologne [1], developing adequate sub-models for antibody-level evolution and drug effects [2,3]. Furthermore, our approach allows for the integration of new data sources, such as waste-water data, enabling a comprehensive understanding of transmission dynamics. While our agent-based model allows accurate simulations of infection spread and the impact of counter-measures, it requires significant computing resources. To address this challenge, we aim to develop a hybrid model that achieves comparable accuracy to the agent-based model while significantly reducing computational costs. This hybrid approach will integrate agent-based models with Ordinary Differential Equation (ODE) and Partial Differential Equation (PDE) models, providing both high computational efficiency and precision in simulating extensive geographical areas.

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Modelling opinion dynamics under the impact of influencer and media strategies

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Opinion dynamics are mathematically modeled by agent-based models (ABMs) that aim to reproduce how agents (individuals) change their state (opinions). To better represent real-world social systems we develop models to study the role of media and influencers on opinion formations [1] by deriving reduced models in the limit of infinite agents (the mean-field limit) [1, 2, 3, 4], and developing ways of estimating opinions from real data.

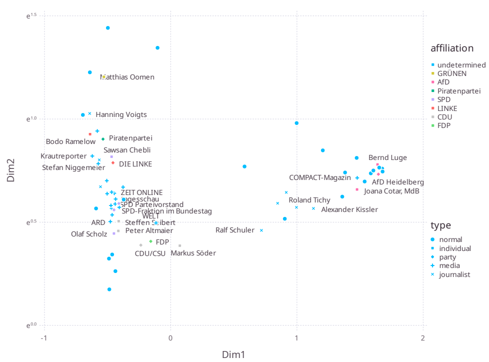

Figure 1: Estimated positions in opinion space of select twitter accounts marked by agent type and political affiliation

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Modeling host-pathogen interactions: infection as a population dynamics problem

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Helminth infections affect a large proportion of the world's population and cause significant morbidity. There are no vaccines against helminths, and the mechanisms by which the body fights off helminth infections are not well-understood. To better understand the immune system response we aim to develop a mathematical model describing the helminth load in different organs of the host as a function of time. As an experimental system, we use murine helminth infection by N.brasiliensis. We abstract infection progression as a state-transition process. The different host organs involved in the infection cycle act as the different states of the system, and the worms are treated as identical and independent particles transitioning from one state to another with certain fixed transition rates and delays. This allows us to simulate the infection process via kinetic Monte Carlo and link the infective dose of larvae to the number of eggs shed to the environment by adult worms from the intestine, which can then be compared against experimental data. We can then use these simulations to generate sufficient training data to employ neural network-based optimization techniques and discover an optimal set of parameters that can quantify the infection process.

Co-evolving networks for opinion and social dynamics in agent-based models

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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[1, 2] 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.

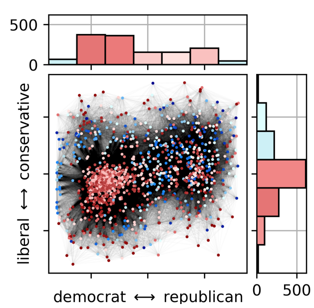

Figure 1: Example of a model simulation started with data from the General Social Survey.

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Exploration Dynamics of 2 random walkers and competition in foraging

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Abstract

Modelling the exploration of space by both complex and very simple bioorganisms has been a very central question at the interplay of biology and random walk theory. In this context, minimal models have focused on memoryless dynamics with simple hopping rules. But the description of the exploration in the case of a population has been much less studied, especially regarding the competition between individuals. We thus consider a minimal model for competition in exploration, studying the case of 2 Brownian walkers evolving in 1-dimensional space. The questions we are interested in are :

- Can we characterize the exploration process, more precisely the time evolution of the number of sites discovered collectively by the walkers ?
- Can we describe the inter-visit times for this collective exploration ?
- What is the interplay between the exploration speed and the relative positions of the walkers ?
- How are discoveries shared between the walkers ?

This last question becomes especially interesting in the context of competitive foraging, where it describes the splitting of ressources between 2 foragers. We explore all these questions in 2 cases : one where sites are only counted on the positive side, and the other where we count all sites. We obtain precise results regarding the exploration process on both cases, and the distribution of the splitting of food between the foragers in the half-line case. This distribution has a form widely known in random walk theory called the arcsine law, whose main features are that equal splitting between the walkers is the less probable outcome, with one walker typically picking up most of the food.

Universal winding properties of chiral active particles

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Abstract: A broad range of active particles can self rotate alongside the usual self propulsion, resulting in a chiral motion with a nonzero angular velocity. It is well-known that the position fluctuations, show only quantitative modifications to the achiral cases, and it is very important to identify observables that preserves signatures of chirality. In this regard, I will discuss the winding properties of chiral active motion in two dimensions, and show that these observables show remarkable universal behaviour for a wide range of microscopic chiral dynamics.

Investigating the Coupling of Speed and Persistence in Migrating Cells

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Cell migration is essential for multiple biological processes, including development, immune response, and tumor invasion. Cells migrate either in an adhesion-independent, contractile amoeboid mode, in a mesenchymal mode, where they adhere to and pull on the surrounding extracellular matrix to move forward, or in a mixture of both modes. A common characteristic across migrating cells is the coupling of speed and persistence, which is described in an universal coupling law of persistence and speed (p-v-coupling). Interestingly, these three parameters (speed, persistence and their coupling) define the capacity of cells to find objects. Furthermore, a migrating cell population exhibits a heterogeneous distribution of cells with a variety of structural and dynamic phenotypes with respect to their speed, persistence or p-v-coupling strength, giving the cells the ability to tune their search behavior.
It is our aim to characterize this heterogeneity in persistence, speed, and p-v-coupling, and to investigate factors which influence these distributions. Therefore, we used 2D live cell imaging to track migrating retinal pigment epithelial cells (hTERT-RPE1 cells), allowing us to calculate dynamic parameters and their coupling. We confirmed that hTERT-RPE1 cells migrating in a mesenchymal manner, follow the p-v-coupling. Additionally, we implemented a pixel classification-based workflow to segment migrating hTERT-RPE1 cells and extract structural parameters like cell eccentricity. In this way, we correlate the structure of a migrating cell to its speed and persistence.

SOKOBAN random walk on the Bethe lattice

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`With persistence a drop of water hollows out the stone' goes the ancient Greek proverb. Yet, canonical models of percolation do not consider the impact of a tracer on its environment. To address this, I employ the Sokoban model [1] in which a randomly moving tracer can push obstacles, one at a time, in its direction of motion. It is unclear how this newfound ability affects percolation in disordered media. To probe into this subject, I study how the escape probability of a Sokoban tracer on the Bethe lattice [2] depends on obstacle density. I determine this probability exactly and show that it undergoes a second-order phase transition. The critical density is lower than the corresponding percolation threshold. This indicates that even a limited ability to push obstacles facilitates escape on the Bethe lattice. Interestingly, this conclusion does not generalize straightforwardly: it was previously shown that the Sokoban always confines itself on the 2D square lattice [1]. I discuss the similarities and differences between these two cases, and postulate regarding Sokoban behavior on other lattices and in higher dimensions.

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Similarities between waves in phononic metamaterials and knowledge dissemination

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Waves in metamaterials and knowledge in society disperse but also dissipate based on distance from the node of generation. There are similarities worth noting and can form the basis for a quantitative analogy which may render the understanding of one contingent upon and feasible through the other. I will be discussing the similarities and differences and will draw upon the analogy to allude to certain problems and possible solutions for the latter based on the former.

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Multi-scale modeling of the chromatin fiber: coupling biophysics and optogenetics

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Inside the nucleus of eukaryotes, DNA is compacted in a structure called chromatin. Many experimental analyses have demonstrated a strong interplay between spatiotemporal structure and epigenetics. As a consequence, the mechanical properties of DNA play a crucial role in many fundamental processes like transcription, replication and DNA reparation. Despite the mechanical properties have been study extensively in vitro, few is known about the mechanical properties of chromatin in vivo. The way these properties are regulated and how they impact the large-scale structure is still not well understood.

Recently the team of Daniel Jost ('Physical Biology of Chromatin', LBMC) has developed a collaboration with Gaël Yvert (LBMC) who is developing an optogenetics tool called LiCre that allow us to probe the contact probability of DNA in vivo. The goal of my PhD thesis will be to develop physical models of chromatin in vivo. And use these models, to orient the optogenetic protocols and interpret the experimental data. The goal is to infer the mechanical properties of chromatin in vivo at different spatial and temporal scales.

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Stochastic bubble dynamics in phase-separated scalar active matter

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In active Brownian particle systems, phase separation is accompanied by the emergence of vapor bubbles within liquid domains. Using large-scale particle-based simulations, we study the stochastic dynamics of these bubbles and find that most nucleate, grow, and dissolve within liquid domains. We show that their area dynamics can be described by a Langevin equation with a constant negative drift and noise proportional to the perimeter, fully characterizing bubble area and lifetime statistics. Additionally, we develop a lattice-gas model that captures the observed decrease in bubble asphericity with increasing area. These findings provide new insights into phase separation in active matter and highlight limitations in current continuum theories.