Search and problem solving by random walks: drunkards vs quantum computers

672. WE-Heraeus-Seminar

May 28 – June 1, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

Introduction

The Wilhelm and Else Heraeus Foundation (Wilhelm und Else Heraeus-Stiftung) is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. To German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Scope of the 672. WE-Heraeus-Seminar:

The main aim of the workshop is to discuss first detection/arrival problems for quantum and classical walks, for example, on a graph, and possible optimisation of search protocols. We believe that better understanding parallels and fundamental differences between classical and quantum - in this particular context - will open the avenue towards solutions of many problems in the now emerging area of quantum information technology. The planned workshop serves this goal by bringing together the two communities of scientists working on classical and quantum walks.

Scientific Organizers:

Prof. Dr. Sergey Denisov — Universität Augsburg, Germany
E-mail sergey.denisov@physik.uni-augsburg.de

Prof. Dr. Eli Barkai — Bar-Ilan University, Ramat Gan, Israel
E-mail barkaie@biu.ac.il

Prof. Dr. Tamás Kiss — Wigner Research Centre for Physics, Budapest, Hungary
E-mail kiss.tamas@wigner.mta.hu

Introduction

Administrative Organization:

Stefan Jorda Martina Albert	Wilhelm und Else Heraeus-Stiftung Postfach 15 53 63405 Hanau, Germany

Phone	+49 (0) 6181 92325-0
Fax	+49 (0) 6181 92325-15
E-mail	lang@we-heraeus-stiftung.de
Internet	www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 (0) 2224 9010-120

Phone	+49 (0) 2224 9010-113 or -114 or -117
Fax	+49 (0) 2224 9010-130
E-mail	gomer@pbh.de
Internet	www.pbh.de

Taxi Phone +49 (0) 2224 2222

Registration:

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

Door Code:

(Key symbol button) 2 6 7 2 #
For entering the Physikzentrum
during the whole seminar

Program

Program

Sunday, May 27, 2018

17:00 – 21:00	Registration	
18:30	*BUFFET SUPPER / Informal get together*	

Monday, May 28, 2018

08:00	*BREAKFAST*	
09:00 – 09:15	Sergey Denisov Eli Barkai Tamás Kiss	**Opening and welcome**
09:15 – 10:00	Igor Jex	**Perturbed quantum walks**
10:00 – 10:45	Cécile Mailler	**The monkey walk: a random walk with reinforced relocations**
10:45 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Viv Kendon	**Optimisation using continuous-time quantum walks**
11:45 – 12:30	Ralf Metzler	**Molecular search in gene regulation: facilitated diffusion and the next steps**
12:30	**Conference Photo** (in front of the Physikzentrum, main entrance)	
12:40	*LUNCH*	

Program

Monday, May 28, 2018

14:30 – 14:35	Reinhard F. Werner	**Colloquium**
14:35 – 15:30	Reinhard F. Werner	**Walking the Quantum Way**
15:30 – 16:00	Christopher Cedzich	**Propagation of quantum walks in electric fields**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Francisco Alberto Grünbaum	**Is thinkin about classical walks a help or a hindrance when dealing with quantum walks?**
17:15 – 17:45	Luis Velázquez	**Recurrence splitting rules for random and quantum walks**
18:30	*DINNER*	

Program

Tuesday, May 29, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	Peng Xue	**Observation of topological edge states in parity-time-symmetric quantum walks**
09:45 – 10:30	Salvador Elias Venegas-Andraca	**Quantum walk-based algorithms, entanglement and quantum annealing**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Peter Hänggi	**Quantum-Thermodynamics: Aspects of quantum work and heat**
11:45 – 12:30	Todd A. Brun	**Effects of raph symmetry on quantum walks**
12:30	*LUNCH*	
14:30 – 14:45	Sidney Redner	**Colloquium**
14:45 – 15:30	Sidney Redner	**Finding targets the random way**
15:30 – 16:00	Carlos Mejia-Monasterio	**Search processes in confined geometries**
16:00 – 16:15	*COFFEE BREAK*	
16:15 – 17:00	Sergey Flach	**Nonlinear disordered discrete time quantum walks**
17:00 – 17:45	Abhishek Dhar	**First return problem of a quantum particle with quasi-Zeno dynamics**
18:00	*DINNER*	
19:00 – 21:00	**Poster session I**	

Program

Wednesday, May 30, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	David Kessler	**Introduction to first quantum detection problems**
09:45 – 10:30	Vasily Zaburdaev	**Planar Lévy-walk bridges: an approach to home-range search and foraging**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Elena Agliari	**Search and diffusion of leucocytes on lab-on-chip**
11:45 – 12:30	Lorenzo Marrucci	**Photonic quantum walks in a single optical beam**
12:30	*LUNCH*	
14:00 – 19:00	**Excursion** (leisurely hike in the vicinity)	
19:00	*HERAEUS DINNER* *(cold & warm buffet, free beverages)*	

Program

Thursday, May 31, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	Stefan Boettcher	**Exploring quantum walks and quantum search algorithms with the renormalization group**
09:45 – 10:30	Mikhail Ivanchenko	**Quantum jumps on Anderson attractors**
10:30 – 10:45	*COFFEE BREAK*	
10:45 – 11:30	Yoav Lahini	**Correlated quantum walks- from photons to ultra-cold atoms**
11:30 – 12:00	Denis Grebenkov	**Search for a small target in biological cells: the necessity to go beyond mean rates**
12:00 – 12:30	Sidney Redner	**The Dynamics of Stochastic Foraging**
12:30	*LUNCH*	
13:50 – 14:30	Sonja Barkhofen	**Time-Multiplexed Photonic Quantum Walks with a 4-dimensional Coin**
14:30 – 15:15	Subinay Dasgupta	**Some aspects of the first passage problem in quantum systems**
15:15 – 16:00	János Asbóth	**Recurrence time in iterated open quantum dynamics**
16:00 – 16:15	*COFFEE BREAK*	
16:15 – 17:00	Gleb Oshanin	**Power spectral density of a single trajectory : Quantifying an ensemble by its random elements**
17:00 – 17:45	Shlomi Reuveni	**First passage under restart**
18:00	*DINNER*	
19:00 – 21:00	**Poster session II**	

Program

Friday, June 1, 2018

08:00	*BREAKFAST*	
09:00 – 09:45	Olivier Bénichou	**First-passage times of Markovian and non-Markovian random walks**
09:45 – 10:30	Andrea Alberti	**Discrete-time quantum walks with neutral atoms in optical lattices**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Felix Thiel	**The spectral dimension controls the decay of the quantum first detection probability**
11:30 – 11:45	Sergey Denisov Eli Barkai Tamás Kiss	**Closing remarks and poster awards**
12:00 – 13:30	*LUNCH*	

End of the seminar *and FAREWELL COFFEE* ***/ Departure***

Please note that there ***will be*** *dinner at the Physikzentrum on Friday evening for participants leaving the next morning!*

Posters

Posters

P01	Enrique Abad	**Survival probability of random walkers in growing domains**
P02	Sonja Barkhofen	**Time-Multiplexed Photonic Quantum Walks with a 4-dimensional coin**
P03	Anna Bodrova	**Scaled Brownian motion with resetting**
P04	Adam Callison	**Continuous-Time Quantum-Computing: Finding spin-glass ground-states using Quantum Walks**
P05	Alessio D'Errico	**Probing Topological phases in quantum walks with spatial modes of light**
P06	Aurél Gábris	**Benchmarking multi-walker interference in a quantum walk simulator**
P07	Tobias Geib	**The topological classification of one-dimensional symmetric quantum walks**
P08	Adam Glos	**Impact of the malicious input data modification on the efficiency of quantum algorithms**
P09	Ru Hou	**Biased continuous-time random walks for ordinary and equilibrium cases: facilitation of diffusion, ergodicity breaking and ageing**
P10	Orsolya Kálmán	**Quantum state matching of qubits via measurement-induced nonlinear transformations**
P11	Miklós Kornyik	**Asymptotics of random density matrices**

Posters

P12	Diego Krapf	**Anomalous Diffusion on the Surface of Mammalian Cells**
P13	Aanjaneya Kumar	**Reachability of Random Walkers on Scale-Free Networks**
P14	Łukasz Kuśmierz	**Efficient search with Lévy walks emerges from stochastic optimization**
P15	Merab Malishava	**Anderson Localization of Two Interacting Particles Using Discrete-Time Quantum Walks**
P16	Jan Mareš	**Asymptotic trapping in disrupted quantum walks on carbon nanotube structures**
P17	Dror Meidan	**Evading Detection: The S_∞ Problem**
P18	Nicolas Moutal	**First exit time distribution for diffusion on an interval with multiple semi-permeable barriers**
P19	Arnab Pal	**First Passage Under Restart**
P20	Vladimir Palyulin	**Systematic comparison of the search properties of Lévy walks and Lévy flights**
P21	Pavlo Pyshkin	**Quantum computation with trotterized fermionic linear optics**
P22	Somrita Ray	**Stochastic thermodynamics of periodically driven systems: Fluctuation theorem for currents and unification of two classes**

Posters

P23	Tal Robin	**Single-Molecule Theory of Enzymatic Inhibition Predicts the Emergence of Inhibitor-Activator Duality**
P24	Matteo Rossi	**Continuous-time quantum walks on graphs with dynamical noise**
P25	Alexander Sauer	**Prevention of Side-Channel Attacks in Timebin-Entanglement Based QKD Protocols**
P26	Jaeoh Shin	**Surface-assisted search dynamics of a reactant**
P27	Renat Sibatov	**Hopping in quasi-fractal superlattices of graphene quantum dots**
P28	Vittoria Sposini	**Diffusing diffusivity VS generalised grey Brownian motion. Two models for diffusion in complex environments.**
P29	Helena Stage	**Anomalous metapopulation dynamics on scale-free networks**
P30	Tereza Štefková	**Quantum walks on the Manhattan lattice and the L-lattice**
P31	Marek Teuerle	**Scaling limits of Lévy walks with random rests**
P32	Ihor Vakulchyk	**Anderson localization in generalized discrete time quantum walks**
P33	Kunkun Wang	**Experimental investigation of quantum witness and Leggett-Garg inequality**

P34	Kay Wiese	**Generalized arcsine laws for fractional Brownian motion**
P35	Lei Xiao	**Observation of topological edge states in parity-time-symmetric quantum walks**
P36	Ruoyu Yin	**Quantum walks on a perturbed ring: The “return” problem**

Abstracts of Lectures

(in chronological order)

Quantum walks and perturbations

T. Nitsche[1], S. Barkhofen[1], R. Kruse[1], L. Sansoni[1], Silberhorn[1], M. Štefaňák[2], A. Gábris[2], V. Potoček[2], I. Jex[2], and T. Kiss[3]

[1]*University of Paderborn, Applied Physics, Warburger Straße 100, 33098 Paderborn, Germany*

[2] FNSPE, CTU in Prague, Břehová 7, 115 19 Praha

[3]*Wigner Research Center for Physics, SZFKI, Konkoly-Thege M. u. 29-33, H-1121 Budapest, Hungary*

Coherent transport of excitations along chains of coupled quantum systems represents an interesting problem with a number of applications ranging from quantum optics to solar cell technology. One convenient tool for studying such processes are quantum walks. Under realistic situations quantum walks, as any genuine quantum evolution, suffers from imperfections. The influences of imperfections on quantum walks can be model in a number of ways. Amon others phase noise and percolation – the random formation or breaking of links between nodes – was studied is quite detail [1-5]. We present several problems involving percolated walks and walks with phase noise including an all optical implementation of a quantum walk differing from the previous experiments by achieving dynamical control of the underlying graph structure and hence representing the simplest walk dynamics on a percolated graph. We demonstrate the evolution of the quantum walk over six double steps, revealing the intricate interplay between the internal and external degrees of freedom. Next we report on the influence of percolation on the efficiency of transport, modelled by a quantum walk, on a ring. We show how the efficiency of a lazy walk can be restored when dynamical percolation is allowed. We comment on the general theory used to treat open system dynamics and point several general features and latest experiment.

References

[1] G. Grimmett, 1999 Percolation, Die Grundlehren der mathematischen Wissenschaften in Einzeldarstellungen (Springer, New York)
[2] G. Leung, P. Knott, J. Bailey and V. Kendon, New J. Phys. 12 (2010) 123018
[3] F. Elster, S. Barkhofen, T. Nitsche, J. Novotný, A. Gábris, I. Jex, Ch. Silberhorn, Scientific Reports 5 (2015) 13495
[4] M. Štěfaňák, J. Novotný, I. Jex, New J. Phys. 18 (2016) 023040
[5] A. Schreiber, K. N. Cassemiro, V. Potoček, A. Gábris, I. Jex, Ch. Silberhorn, Phys. Rev. Lett. 106 (2011) 180403
[6] T. Nitsche, S. Barkhofen, R. Kruse, L. Sansoni, M. Štefaňák, A. Gábris, V. Potoček, T. Kiss, I. Jex, Ch. Silberhorn, arXiv:1803.04712

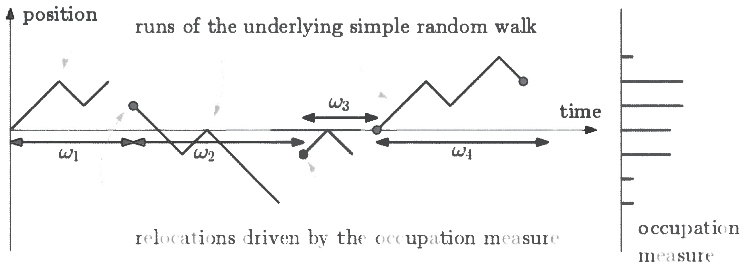
The monkey walk:
a random walk with reinforced relocations.

C. Mailler[1] and G. Uribe-Bravo[2]

[1]University of Bath, Bath, UK
[2] Universidad Nacional Autonoma de Mexico, Mexico City, Mexico
E-mail: c.mailler@bath.ac.uk

The monkey walk is a random walk that was introduced by Boyer and Solis-Salas [1] as a good model for animal foraging behaviour; in particular, they showed that this model nicely fits some data taken on free-ranging Capuchin monkeys. In a series of papers, Boyer and co-authors [1-2] show that this walk exhibits a slow-diffusive behaviour. In this talk, I will show how this model can be studied using a coupling with a random tree that we call the weighted recursive random tree (WRRT), and how this approach is a powerful tool to prove and extend the conjectures of Boyer et al.

The monkey walk is a discrete time process that evolves as follows: fix a sequence of i.i.d. random variables that we call the run-lengths, the monkey walks performs a runs of simple random walks (of lengths given by the run-lengths), and between two runs, it jumps to a site it has already visited in the past, and chooses which site with probability proportional to the number of past visits at that site. The more the monkey has visited a site, the more likely it is to go back there again; this is why we use the term of *reinforced relocations*.



We can extent the model by replacing the simple random walk runs by runs of a Markov process (in discrete or continuous time), and prove a central limit theorem for the position of the monkey at large time, as well as a local limit theorem and large deviations. We can also prove convergence of the occupation measure.

References

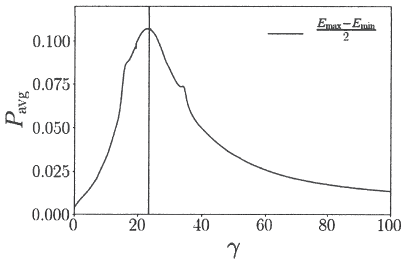
[1] D. Boyer and C. Solis-Salas, Phys. Rev. Lett. **112**, 240601 (2014)
[2] D. Boyer and I. Pineda, Phys. Rev. E **93**, 022103 (2016)

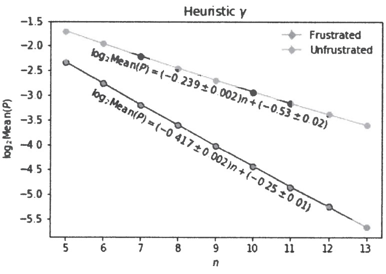
Optimisation using continuous-time quantum walks

A. Callison[1] and V. Kendon[2]

[1]Imperial College London, UK
[2]Durham University, UK
E-mail: viv.kendon@durham.ac.uk

Continuous-time quantum walks and adiabatic quantum computing (AQC) can solve the same problems using the same Hamiltonians. They differ in the time evolution that transforms the easy to prepare initial state to the final ground state that encodes the solution. AQC slowly varies the Hamiltonian from initial to final state, staying close to the ground state throughout. Continuous-time quantum walks apply both Hamiltonians at the same time, in carefully chosen proportions. In previous work [1] on the search problem, hybrid strategies in which the time evolution is an interpolation between quantum walk and AQC are shown to be the best choice for imperfect hardware. In this work, we apply continuous-time quantum walks to more realistic hard problems based on spin glasses. We show numerically that quantum walks can find the ground states better than classical guessing, and compare the performance on random instances of frustrated and unfrustrated spin systems. We also find that simple heuristics are sufficient to tune the proportion (gamma) of the quantum walk and problem Hamiltonians (see figure), an important consideration for solving real optimisation problems. We only expect to obtain a polynomial improvement for these exponentially hard problems, but for real world computation this provides a significant advantage.





Left: success probability vs gamma for a frustrated spin glass (red) and heuristic (blue) mean energy spread; Right: mean success probablity vs number of qubits for frustrated (blue) and unfrustrated (red) spin glasses, averaged over 10,000 random instances per data point.

References

[1] J. G. Morley, N. Chancellor, S. Bose, V. Kendon, arXiv:1709.00371 (2017)

Molecular search in gene regulation: facilitated diffusion and the next steps

Ralf Metzler

University of Potsdam, Institute of Physics & Astronomy, 14476 Potsdam, Germany

The regulation of the genetic information stored in DNA is controlled by DNA binding proteins called transcription factors (TFs). TFs locate their designated binding site by using the naturally available ``fuel" provided by their thermal environment. It was realised relatively early that the TFs do not simple diffuse three-dimensionally to locate their target site on the DNA. Rather, they perform facilitated diffusion [1], i.e., they utilise the topology of the DNA to enhance the efficiency of their search. The facilitated diffusion model will be introduced and recent evidence from single molecule experiments discussed. In particular, the role of the conformations of DNA will be addressed and shown that the search process is improved when the DNA is more coiled [2].

Apart from the TF location to the target site, it will be discussed how the expression of one gene controls another downstream gene, in particular, how the accuracy of this control can be effected [3]. The next step is then to take the above models, designed for dilute scenarios in typical in vitro experiments, to the more complex environment of living cells [4]. Moreover, I will introduce the concept of the few encounter limit relevant to determine the regulation dynamics in molecular signalling processes [5].

Finally, the crowded state of the cellular cytoplasm by large molecules will be addressed [6] and shown how aspects of the dynamics and the conformation of DNA are changed. Knowledge about these facts is important to understand how gene regulation works in living cells.

References

[1] PH v Hippel and O Berg, J Biol Chem 264, 675 (1989).

[2] B vd Broek, MA Lomholt, S-MJ Kalisch, R Metzler, and GJL Wuite, Proc Natl Acad Sci USA 105, 15738 (2008); MA Lomholt, B vd Broek, S.-M. J. Kalisch, GJL Wuite, and R Metzler, Proc Natl Acad Sci USA 106, 8204 (2009).

[3] O Pulkkinen and R Metzler, Phys Rev Lett 110, 198101 (2013).

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Walking the Quantum Way

Reinhard F. Werner[1]

[1]*Institute for Theoretical Physics, Leibniz Universität Hannover, Germany*
E-mail: Reinhard.Werner@itp.uni-hannover.de

This colloquium talk will give an introduction to quantum walks, intended especially (but not exclusively) for those participants who are less familiar with quantum theory.
On the one hand, quantum mechanics makes probabilistic statements, which should be immediately understandable to probabilists. On the other, the probabilities are computed differently, using the Hilbert space structure, which entails some major differences to the classical world. I will then describe the mathematical setting of quantum walks, and how such systems are realized in the lab [1].
The general structure of walks is an interplay between the requirements of unitarity and locality (no very long jumps). This has a constructive side, i.e., a systematic way to build such systems from "shift" operations and "coin" operations, and also implies a non-trivial topological classification measured by an index [2]. I will interpret this by a quantized version of Claude Shannon's theory of juggling [3].
Quantum walks can propagate faster than their classical counterparts. As one instance of this I will discuss translation invariant walks on a lattice, and show how to compute the asymptotic position distribution in ballistic scaling [4]. I will also give examples of speedup from walks of Szegedy-type [5], which have been discussed in the context of search problems. Propagation is also closely linked to the spectrum of the walk operator, and I will briefly sketch the known general connections.
Finally, I will discuss first passage and return problems. The Heisenberg Effect (observation requires disturbance) forces us to make a decision about how to include the dynamical effects of monitoring the system. I will describe one setting [6] in which a simple spectral criterion for recurrence can be obtained.

References

[1] M. Karski et al., Science **325,** 174 (2009)
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Propagation of quantum walks in electric fields

C. Cedzich[1,2], T. Rybár[1], A. H. Werner[3,4], A. Alberti[5], M. Genske[5], and R. F. Werner[1]

1 Institut für Theoretische Physik, Leibniz Universität Hannover, Appelstr. 2, 30167 Hannover, Germany
2 Institut für Theoretische Physik, Universität zu Köln, Zülpicher Straße 77, 50937 Köln, Germany
3 QMATH, Department of Mathematical Sciences, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark,
4 NBIA, Niels Bohr Institute, University of Copenhagen, Denmark
5 Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, 53115 Bonn, Germany

We study one-dimensional quantum walks in a homogeneous electric field, which correspond to discrete time standard walks where after each step a phase depending linearly on position is applied. We show that the propagation properties of the system depend sensitively on the electric field Φ. This dependence exemplifies the connection between spectral and dynamical properties, as established, e.g. by the RAGE theorem. We distinguish the following scenarios: (1) When $\Phi/(2\pi)=n/m$ is an irreducible fraction, there is a revival after m or $2m$ steps, which is exponentially sharp in m. This is followed by a ballistic expansion. (2) When Φ has very good rational approximations, as provided by continued fractions, there is a hierarchy of time scales, each coming with a sharper revival and an arbitrarily large ballistic excursion. (3) In the very irrational case we find Anderson localization, i.e., a complete system of discrete, exponentially decaying eigenfunctions. We conjecture that this holds with probability one for random fields.

References

[1] C. Cedzich, T. Rybár, A. H. Werner, A. Alberti, M. Genske, and R. F. Werner. Propagation of quantum walks in electric fields. Phys. Rev. Lett., 111:160601, 2013. arXiv:1302.2081.

Is thinking about classical walks a help or a hindrance when dealing with quantum walks?

F. Alberto Grünbaum

University of California, Berkeley, Department of Mathematics, Berkeley, CA, USA
E-mail: albertogrunbaum@yahoo.com

Some ideas from classical walks, such as the use of generating functions for the probabilities of "returns to the initial state in n steps" as well as these same return probabilities but "for the first time" have been extended to the quantum case and shown to satisfy the "same" relations that hold in the older setup. Moreover some of these "Schur functions" can be seen to be useful not only in the study of recurrence properties of these quantum walks but also as a tool in a "topological classification of quantum walks".

I will discuss a few other classical notions both for discrete time random walks as well as for Brownian motion, the Ornstein-Uhlenbeck process etc. and raise the question mentioned in the title.
Under this umbrella I will mention a few points of contact between classical probability and topics that may be importance in the study of quantum walks.

This talk could/should have connections with the talks of Reinhard Werner and Luis Velazquez, and maybe others too.

Recurrence splitting rules for random and quantum walks

C. Cedzich[1], F. A. Grünbaum[2], L. Velázquez[3], A. H. Werner[4], R. F. Werner[1]

[1]Leibniz Universität Hannover, Hannover, Germany
[2] UC Berkeley, Berkeley, USA
[3] Universidad de Zaragoza, Zaragoza, Spain
[4] University of Copenhagen, Copenhagen, Denmark

A monitored approach to quantum recurrence recently proposed [1,2] has revealed deep connections with a very well known mathematical tool: the Schur functions. This has been the origin of a rich interplay between quantum physics and classical mathematical areas, source of surprising results in discrete time quantum dynamics [1,2,4], as well as novel approaches to mathematical problems leading to advances in approximation theory and harmonic analysis [3,4].

In this talk we will present one of the many Schur functions' virtues behind their wide impact: the ability of Schur functions to mimic certain splittings of underlying operators. When applied to Schur functions related to evolution operators in classical random walks, quantum walks and open quantum walks, this results in splitting rules playing the role of divide-and-conquer methods for the study of recurrence in such discrete time systems. Some striking consequences of these splitting techniques will be shown. We will also point out other possible uses of the Schur technology in the realm of quantum walks.

References

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[4] F. A. Grünbaum, L. Velázquez, Adv. Math. **326**, 352-464 (2018)

Observation of topological edge states in parity-time-symmetric quantum walks

Peng Xue[1, 2]

[1] *Department of Physics, Southeast University, Nanjing 211189, China*
[2] *Beijing Computational Science Research Center, Beijing 100084, China*

The study of non-Hermitian systems with parity-time (PT) symmetry is a rapidly developing frontier in recent years. Experimentally, PT-symmetric systems have been realized in classical optics by balancing gain and loss, which holds great promise for novel optical devices and networks. Here we report the first experimental realization of passive PT-symmetric quantum dynamics for single photons by temporally alternating photon losses in the quantum walk (QW) interferometers. The ability to impose PT symmetry allows us to realize and investigate Floquet topological phases driven by PT-symmetric QWs.

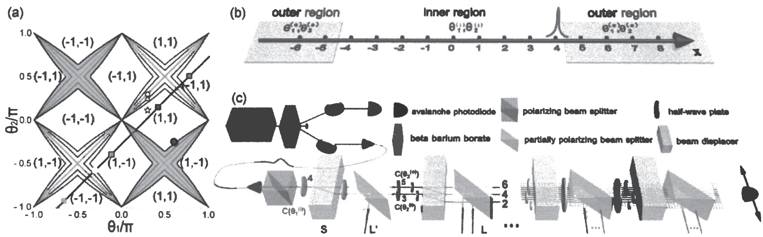

Fig1. Phase diagram and experimental scheme for non-unitary QWs with alternating losses. (a) Phase diagram, (b) The inner and outer regions for the inhomogeneous non-unitary QW. (c) Experimental setup.

We observe topological edge states between regions with different bulk topological properties and confirm the robustness of these edge states with respect to PT-symmetry-preserving perturbations and PT-symmetry-breaking static disorder. Our results pave the way for realizing quantum mechanical PT-synthetic devices and augur exciting possibilities for exploring topological properties of non-Hermitian systems using discrete-time QWs.

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Quantum Walk-based Algorithms, Entanglement and Quantum Annealing

S.E. Venegas-Andraca[1] , W. Cruz-Santos[2] and E. Campos-Espinoza[1]

[1]*Tecnologico de Monterrey, Monterrey, Mexico*
[2] *UAEM, Chalco, Mexico*

Quantum walks were originally developed as quantum-mechanical counterparts of classical random walks. In the early days of this cross-disciplinary research field, quantum walks were used just as a mathematical tool to develop sophisticated algorithms. Later on and in stark contrast to the algorithmic properties of classical random walks, it was proved that quantum walks constitute a universal model for quantum computation.

Most quantum walk-based algorithms have benefited from the diffusion properties of this model of computation; however, it remains an open area of research to identify and characterize strategies for algorithm development based on quantum walks that take advantage of quantum mechanical phenomena like quantum entanglement and quantum tunneling.

Quantum entanglement is expected to play a key role in the formulation of quantum algorithms that are faster than their classical counterparts. Although some aspects of quantum entanglement and computational speed up have been studied, we lack a general framework to explicitly manipulate quantum entanglement for building quantum algorithms, being the ultimate purpose of such framework to provide quantum programmers with mathematical descriptions and subroutines in order to build algorithms for solving complex problems.

The role of entanglement in quantum walks is an open area of research. Motivated by the wish to further study the effect of entanglement in discrete quantum walks, in the first part of our talk we shall present a preliminary framework for manipulating quantum walk parameters via quantum entanglement together with a succinct yet complete review of the state-of-the-art on the role of quantum entanglement in the definition and dynamics of quantum walks.

The second part of our talk will consist of briefly introducing the quantum annealing model of computation, which has become a most successful platform for the development of quantum machine learning algorithms, followed by an analysis of known similarities and differences of this model of computation and quantum walks.

Quantum-Thermodynamics: Aspects of quantum work and heat

Peter Hänggi[1]

[1]University of Augsburg, Dept. Physics, 86135 Augsburg, Germany
E-mail: hanggi@physik.uni-augsburg.de

The issue of doing thermodynamics in the quantum regime *in* and *far* from thermal equilibrium is in the limelight of several active research areas. This is so because of the recent interest of considering all types of nano-systems placed either in isolation or in presence of coupling to environments, thereby allowing for particle and heat exchange. Doing so, opens new avenues for the design and its operation of quantum motors and quantum heat machines. This comes, however at a considerable prize. First, the system sizes are then typically sufficiently small so that mean values and fluctuations of characteristic quantities can become of the same order. Moreover, commonly familiar classical notions such as work and particularly heat are all but not trivial to deal with in a quantum setting. Even when kept at thermal equilibrium these notions become very tricky and in fact are still not settled uniformly. Thus, in distinct contrast to what one might a priori hypothesize, matters become quite subtle. Therefore, -- *if something can be said at all – it should be stated most clearly.*

A first main problem is that physical quantities such as work and heat are not quantum observables but rather processes. Second, in order to extract numbers one needs to measure quantum mechanically those quantities; -- with quantum mechanics always implying a *back-action* the procedure of obtaining those values for quantum work and/or heat become a formidable task – if at all they can be obtained/measured.

In this contribution I will give the audience an introduction (flavor) why things are not as simple as expected and point out various subtleties and pitfalls when engaging into quantum thermodynamics in, near and far away from thermal equilibrium.

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Effects of Graph Symmetry on Quantum Walks

T.A. Brun[1]

[1]*University of Southern California, Los Angeles, California, USA*
E-mail: tbrun@usc.edu

Quantum walks on graphs are a paradigm for a broad class of quantum algorithms, as well as being fascinating objects of study in their own right. While similar in mathematical form to classical random walks, they display radically new and different behavior because of destructive and constructive interference effects. In analyzing such walks, we are often concerned with their hitting or mixing times. Even defining these time scales leads to subtle questions for quantum walks [1,2].

One curious result of interference is that the hitting time can be strongly affected by the symmetry of the graph [2-5]. Graph symmetry can cause a quantum walk to be confined to a low-dimensional subspace of the full Hilbert space; in some cases, these subspaces have the structure of a simplified graph themselves, so-called *quotient graphs* [4]. Symmetry can cause a quantum walk to hit exponentially faster than the corresponding random walk [4]; but it can also make the hitting time *infinite* [2-3]. Both of these effects can be exploited to produce quantum algorithms.

I will discuss these effects for both discrete-time and continuous-time [5-7] walks, and how they differ in the two cases. I will also touch on some open questions about this topic, such as how to extend it to multiparticle quantum walks [8]; and will look at symmetry effects in a very different context, where quantum walks on lattices serve as models of relativistic particles in spacetime [9].

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Finding Targets The Random Way

Sid Redner

Santa Fe Institute, Santa Fe, New Mexico, USA

How do diffusing particles find a target? This scenario typifies first-passage processes, where *first* reaching a target is paramount. I'll first present connections between first passage and electrostatics. These ideas will be illustrated with the first-passage properties of: (i) a fixed interval, and (ii) a growing interval. For the latter, deep results can be obtained by simple means. Next, I'll discuss the trapping efficiency of diffusing particles by: (i) a perfectly absorbing, and (ii) a defective sphere—the latter is relevant for cell chemoreception. Finally, I'll determine the survival probability of a diffusing lamb that is chased by N diffusing predators in one dimension, where intriguingly rich dependence on N arises.

Search processes in confined geometries

Carlos Mejia-Monasterio

Technical University of Madrid
Av. Complutense s/n, 28040 Madrid SPAIN

Search processes are ubiquitous in Nature: in order to survive, predators have to hunt the prey and the prey has to forage. In order to convert into required reaction products, the reactants involved in chemical or biochemical reactions have first to find each other. In many biophysical processes ligands search for binding sites, proteins seek the target sequences on DNA's, etc. In this talk we discuss random and certain directed stochastic search processes in bounded domains, and analyse the influence of the boundary on the First Passage Time Distribution (FPTD). Despite the compactness of the FPTD, the fluctuations of the Mean First-Passage Time (MFPT) strongly depend on the initial position of the searcher. In particular, when the search starts close to the target the MFPT becomes the less probable value of any single search. The influence of confinement in directed searches where the agent receives information about the location of the target will also be discussed for the case of *infotaxis* olfactory searches.

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Nonlinear Disordered Discrete Time Quantum Walks

S. Flach

Center for Theoretical Physics of Complex Systems
Institute for Basic Science, Daejeon, South Korea

Discrete quantum walks (DQW) are a main tool in quantum computing research. At the same time, they are fascinating mathematical models on lattices with unitary operators involving only nearest neighbor coupling, and thus with a speedup in certain comptutations up to two orders of magnitude as compared to Hamiltonian based dynamics. I will introduce the translationally invariant DQW and its massive Dirac two-band structure. I will then introduce disorder and demonstrate the existence of, and control over Anderson localization [1]. Finally I will generalize the disordered DQW by adding nonlinear terms to the unitary operations. As a result, wave packet dynamics is characterized by a slow subdiffusive destruction of Anderson localization [2]. I will show that we can drive this process to unprecedented times as compared to previous studies. This will allow us to surpass the current computational horizon by a factor of up to 10^3 and check whether the neverending subdiffusion IS keeping its universality beyond the hold horizons, or whether a slowing down effect will be seen as claimed in some publications.

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First return problem of a quantum particle with quasi-Zeno dynamics

Sourabh Lahiri[1], Subinay Dasgupta[2] and Abhishek Dhar[3]

[1]*BIT Mesra, Ranchi, India*
[2]*Department of physics, Calcutta University, Kolkata, India*
[3]*International centre for theoretical sciences, Bengaluru, India*
E-mail: abhishek.dhar@icts.res.in

In recent work, the so-called quasi-Zeno dynamics of a system has been investigated in the context of the quantum first passage problem. This dynamics considers the time evolution of a system that is subjected to a sequence of selective projective measurements made at small but finite intervals of time. This means that one has a sequence of steps, with each step consisting of a unitary transformation followed by a projection. It has been shown that this non-unitary dynamics can be effectively described by two different non-Hermitian Hamiltonians. I will discuss this connection, and an application to the problem of detection of a free quantum particle moving on a one-dimensional lattice, with a detector placed at the origin. We find that results for distribution times for the first detection probability, obtained from the non-Hermitian Hamiltonians, are in excellent agreement with known exact results as well as exact numerics. Interesting finite-size effects are discussed.

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Introduction to First Quantum Detection Problems

David Kessler

Bar-Ilan University, Department of Physics, Ramat Gan, Israel

Planar Lévy-walk bridges: an approach to home-range search and foraging

V. Zaburdaev[1] and **S. Denisov[2]**

[1] MPI for the Physics of Complex Systems, Dresden, Germany
[2]Augsburg University, Augsburg, Germany

Lévy walks are random walks in which the walker moves continuously and with a constant velocity between the reorientation events. The durations of these displacements and correspondingly their lengths are power-law distributed. Lévy walks were shown to be a very successful model to describe a variety of anomalous diffusion dispersal phenomena in physics, biology and ecology [1]. In the context of search, Lévy walks were identified as an optimal strategy for finding rare renewable targets and that boosted the research in Lévy foraging strategies in living organisms [2]. The trend was inherited in robotics, where Lévy algorithms were implemented in robots performing various search tasks.

However, one important aspect intrinsically present in most living systems but also in robotics - the existence of home range - was not considered before in the context of random search. The fact that a bird needs to return to its nest and a robot to its charging station seems obvious, but the implementation of such processes on the model level is a highly non-trivial task (see, e.g. [3]). In this talk, we will introduce the concept of Lévy walk bridges - Lévy walk trajectories returning to the origin after a fixed time. We will show how to tackle the challenge of the efficient bridge generation and how the Lévy walk bridges operate during search. We will discuss what further intriguing problems open up in relation to the introduced concept.

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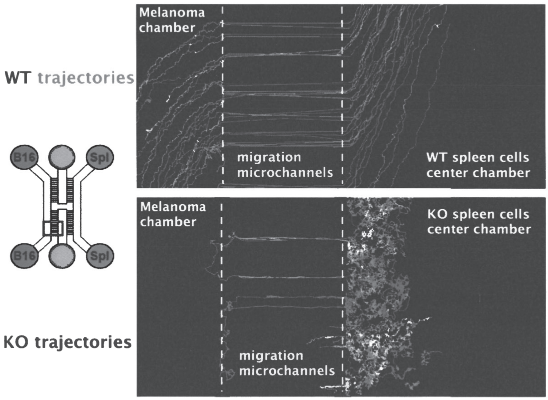
Search and Diffusion of Leucocytes on Lab-On-Chip

E. Agliari[1] and A. Barra[2]

[1]Department of Mathematics, Sapienza University of Rome, Rome, Italy
[2] Department of Mathematics and Physics, Salento University, Lecce, Italy
E-mail: agliari@mat.uniroma1.it

In this work we consider data collected on a microfluidic platform, where immune cells (leukocytes) can move toward a target (cancer cells). In order to investigate the mechanisms driving the mutual crosstalk between cancer and immune cells, we compare the behavior of leukocytes from immunodeficient mice (knockout, KO) and leukocytes from immunocompetent mice (wild-type, WT). The former are shown to perform unbiased and uncorrelated random walks, the latter are shown to perform drifted random walks. Finally, the ability of WT leukocytes to interact each other and possibly enhance their migratory ability toward the insult is investigated exploiting techniques based on the maximum entropy principle.



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Photonic quantum walks in a single optical beam

Lorenzo Marrucci[1]

[1]*Università di Napoli Federico II, Napoli, Italy*
E-mail: lorenzo.marrucci@unina.it

Quantum walks are simple quantum-evolution processes that can reproduce the key qualitative features of many interesting complex real systems. Hence, these processes are at the root of many quantum simulations. A quantum walk can be for example carried out using photons in a variety of possible experimental architectures. The most straightforward and versatile concept is using "real space" for the walk degree of freedom, as in waveguide networks of integrated optics. However, my coworkers and I have recently demonstrated an interesting alternative approach for which the walk degree of freedom is encoded in the internal mode structure of a single light beam [1]. The walk is then physically realized by letting the light beam propagate through a sequence of suitable optical elements exploiting Pancharatnam-Berry phases to couple modes and polarization [1]. An important practical advantage of this approach is that no interferometric stability is needed. Moreover, the required resources scale linearly with the number of steps and it is particularly easy to introduce time-varying actions and external parameters [1]. Hitherto, we have used the orbital angular momentum (OAM) of the light beam, a naturally discrete variable, to give rise to a discrete-time quantum walk on a 1D lattice. This has allowed us to explore experimentally the topological features of certain 1D single-particle systems [2,3]. More recently, we are exploring new approaches that could allow us to simulate 2D lattice systems with only a moderate increase of resources. In this presentation, I will review our recent works on photonic quantum walks and the resulting simulations of topological systems.

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Exploring Quantum Walks and Quantum Search Algorithms with the Renormalization Group

Stefan Boettcher

Emory University, Department of Physics, Atlanta, GA, USA
E-mail: sboettc@emory.edu

We will discuss the implementation of the real-space renormalization group (RG) for quantum walks. For the discrete-time ("coined") quantum walk, these resemble classical random walks, in particular, persistent walks or 2nd-order Markov processes. However, being a unitary process instead entails several aspects not found classically [1,2]. We then illustrate the RG by calculating a few exact results on the spreading of quantum walks on fractal networks. These results seem to generalize in a straightforward manner to arbitrary fractal dimensions. Especially, these would imply a generic bound on the computational complexity of a Grover quantum search algorithm with such a coined walk in terms of the spectral dimension of any network [3]. We finally address some open questions regarding spatially inhomogeneous coins and issues regarding localization (without disorder) that are unique for quantum walks.

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Quantum jumps on Anderson attractors

I. Yusipov, T. Laptyeva and M. Ivanchenko

Lobachevsky University, Nizhny Novgorod, Russia
E-mail: ivanchenko.mv@gmail.com

In a closed single-particle quantum system, spatial disorder induces Anderson localization of eigenstates and halts wave propagation. The phenomenon is vulnerable to interaction with environment and decoherence that is believed to restore normal diffusion. We demonstrate that for a class of experimentally feasible non-Hermitian dissipators, which admit signatures of localization in asymptotic states, quantum particle opts between diffusive and ballistic regimes, depending on the phase parameter of dissipators, with sticking about localization centers. In a diffusive regime, statistics of quantum jumps is non-Poissonian and has a power-law interval, a footprint of intermittent locking in Anderson modes. Ballistic propagation reflects dispersion of an ordered lattice and introduces the second timescale for jumps, resulting in non-nonmonotonous probability distribution. Hermitian dephasing dissipation makes localization features vanish, and Poissonian jump statistics along with normal diffusion are recovered.

Correlated quantum walks- from photons to ultra-cold atoms

Y. Lahini

School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
E-mail: lahini@tauex.tau.ac.il

Quantum walks are unitary processes describing the propagation of quantum particles on lattice potentials. Originally described as a quantum-mechanical analog of the classical random walk, QWs were found to exhibit faster propagation and enhanced sensitivity to lattice parameters due to their coherent nature. These properties generated broad interest in applying QWs to quantum information processing tasks.

Experimentally, QWs have been implemented using a wide array of platforms, including photonics, trapped ions and ultra-cold atoms. The current degree of experimental control of these systems is remarkable: it is possible to prepare an initial state with single-site and single-particle resolution, to control almost every aspect of the lattice potential, and to directly monitor the evolving wave function. Early experiments demonstrated the behavior of single-particle QWs; however, these dynamics can be described by classical wave equations (indeed, some of these experiments were performed with coherent light), and thus cannot display non-classical features. Non-classical behavior can be observed when several indistinguishable particles participate in the QW simultaneously, as was shown both theoretically, and experimentally. Here, **non-classical spatial correlations**—i.e., non-trivial dependencies between the positions of different walkers—emerge due to quantum (bosonic or fermionic) statistics. Recent work has investigated the role of interactions in the two-particle quantum walk, finding that they give rise to even more complex correlated dynamics. These 'strongly correlated' QWs were recently observed experimentally in a system of ultra-cold atoms.

Can the spatial correlations that emerge between several interacting quantum co-walkers be useful for **quantum information processing?** If so – how do, we design such systems?

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Search for a small target in biological cells: the necessity to go beyond mean rates

D. S. Grebenkov[1], R. Metzler[2], and G. Oshanin[3]

[1] Laboratoire de Physique de la Matière Condensée (UMR 7643), CNRS -- Ecole Polytechnique, University Paris-Saclay, 91128 Palaiseau, France

[2] Institute of Physics & Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany

[3] Sorbonne Université, CNRS, Laboratoire de Physique Théorique de la Matière Condensée (UMR CNRS 7600), 4 Place Jussieu, F-75005, Paris, France

The first-passage time (FPT), i.e., the moment when a stochastic process reaches a given threshold value for the first time, is a fundamental mathematical concept with immediate applications. In particular, it quantifies the statistics of instances when biomolecules in a biological cell reach their specific binding sites and trigger cellular regulation. Typically, the first-passage properties are given in terms of mean first-passage times. However, modern experiments now monitor single-molecular binding-processes in living cells and thus provide access to the full statistics of the underlying first passage events, in particular, inherent cell-to-cell fluctuations. We here present a robust explicit approach for obtaining the distribution of FPTs to a small target region in cylindrical-annulus domains, which represent typical bacterial and neuronal cell shapes. We investigate various asymptotic behaviors of this FPT distribution and show that it typically is very broad in many biological situations: thus, the mean FPT can differ from the most probable FPT by orders of magnitude. The most probable FPT is shown to strongly depend only on the starting position within the geometry and to be almost independent of the target size and reactivity. These findings demonstrate the dramatic relevance of knowing the full distribution of FPTs and thus open new perspectives for a more reliable description of many intracellular processes initiated by the arrival of one or few biomolecules to a small, spatially localized region inside the cell.

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The Dynamics of Foraging and Starvation

O. Bénichou[1], U. Bhat[2], M. Chupeau[1], P. L. Krapivsky[3], C. Rager[2], and S. Redner[2]

[1]Laboratoire de Physique Théorique de la Matière Condensée (UMR CNRS 7600), Université Pierre et Marie Curie, 4 Place Jussieu, 75252 Paris Cedex, France
[2]Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, New Mexico 87501, USA
[3]Department of Physics, Boston University, Boston, Massachusetts 02215, USA
E-mail: redner@santafe.edu

What is the fate of a random-walk forager that depletes its environment as it wanders? Whenever the forager lands on a food-containing site, all the food is consumed and the forager becomes fully sated. However, when the forager lands on an empty site, it moves one time unit closer to starvation. If the forager wanders S steps without encountering food, it starves to death. We show analytically that the lifetime of this starving random walk forager scales linearly with S in one dimension by solving an underlying non-Markovian first-passage problem [1,2]. In greater than two dimensions, we present evidence that the lifetime grows quasi-exponentially in S.

We also investigate the role of greed, in which the forager preferentially moves towards food when faced with a choice of hopping to food or to an empty site in its local neighborhood [3]. Paradoxically, the forager lifetime can have a non-monotonic dependence on greed, with different senses to the non-monotonicity in one and in two dimensions. In one dimension, the forager lifetime exhibits a huge peak when greed is negative, while in two dimensions, the maximum lifetime occurs for positive, but not perfect, greed.

Finally, we briefly discuss the role of frugality [4] and myopia [5] on foraging dynamics. Frugality means that the forager does not eat until nutritionally depleted beyond a specified level. Myopia means that the forager sometime does not "see" food at its current site and leaves the food undisturbed.

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Time-Multiplexed Photonic Quantum Walks with a 4-dimensional coin

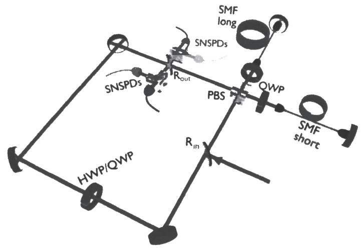
Sonja Barkhofen[1]*, Lennart Lorz[1], Evan Meyer-Scott[1], Thomas Nitsche[1], Václav Potoček[2], Igor Jex[2], Christine Silberhorn[1]

[1]*Applied Physics, University of Paderborn, Warburger Strasse 100, 33098 Paderborn, Germany*

[2]*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 11519 Prague, Czech Republic*

**Sonja.Barkhofen@uni-paderborn.de*

Photonic quantum walk systems serve as a standard model to describe the dynamics of quantum particles in a discretized environment and act as a versatile simulator for complex quantum systems, which are not as readily accessible. However, their experimental realization requires setups with increasing complexity in terms of number of modes and control of the system parameters.



Setup scheme of a time-multiplexed quantum walk architecture based on a Michelson interferometer

Here, we present a photonic quantum walk on a looped Michelson interferometer and demonstrate the benefits of this new interferometric geometry. The time-multiplexing approach provides high homogeneity, precise control of the system parameters and optimal resource efficiency as was shown already for a Mach-Zehnder type setup [1–3]. By exploiting the two different travelling directions in the loop in addition to the two polarizations of the walker we implement a 4D coin space for a 1D walk. Fast electro-optic modulators realising dynamic coin operations enable us to study coupled quantum walks and revivals in finite 1D walks with periodic boundary conditions of programmable size paving the way towards quantum search applications.

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Some aspects of the first passage problem in quantum systems

Subinay Dasgupta[1] **and Abhishek Dhar**[2]

[1]Department of Physics, University of Calcutta, 92 Acharya Prafulla Chandra Road, Kolkata 700009, India

[2] International Centre for Theoretical Sciences, TIFR, Bengaluru 560012, India

E-mail: subinay.dasgupta@gmail.com

We shall address two questions : (i) For a transverse Ising chain at zero temperature, we measure the transverse magnetic moment (per site) at interval of time T . *What is the probability that for each of the first n measurements, the result will be 1?* From the expression for this probability, we show that [1] the response of this system shows a non-analyticity as a function of the external applied field and the time interval of measurement. In contrast to order-disorder phase transitions, this type of phase transition is not a property of the ground state and arises from the Hamiltonian dynamics and quantum mechanical nature of the measurement. A similar measurement-induced phase transition has been predicted [2] for two-level systems also. (ii) Suppose we have a quantum particle moving on a one-dimensional periodic lattice under tight-binding Hamiltonian. Initially, the particle was at site 1 and we have a detecor placed on the same site. The detector is turned on (instantaneously) at interval of time T to check if the particle is still there. *What is the probability that for each of the first n measurements, the particle will be detected?* We shall also consider generalisation to the case [3] when the particle is initially confined to a box of 2 or 3 sites and study the probability of its remaining within the box for the first n measurements.

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Recurrence time in iterated open quantum dynamics

P. Sinkovicz[1], J. Asbóth[1], Z. Kurucz[1] , and T. Kiss[1]

[1] *Institute for Solid State Physics and Optics, Wigner Research Centre, Hungarian Academy of Sciences, Budapest, Hungary*

We show that the recurrence time, i.e., the expected return time, is an integer in a broad class of iterated open quantum dynamical systems in finite dimensional Hilbert spaces. This class is that of unital dynamics, which includes classical Markov chains, unitary discrete time quantum walks, as well as in-between cases with some forms of decoherence. Starting from a pure state, the time evolution is induced by repeated applications of a general quantum channel, in each timestep followed by a measurement to detect whether the system has returned to the original state. We prove[1] that if the superoperator is unital in the relevant Hilbert space (the part of the Hilbert space explored by the system), then the expectation value of the return time is an integer, equal to the dimension of this relevant Hilbert space. We illustrate our results on partially coherent quantum walks on finite graphs. Our work connects the previously known quantization of the expected return time for bistochastic Markov chains and for unitary quantum walks, and shows that these are special cases of a more general statement. The expected return time is thus a quantitative measure of the size of the part of the Hilbert space available to the system when the dynamics is started from a certain state. Moreover, we show that for a more general class of quantum channels the expected return time can be given as the inverse of the weight of the initial state in the steady state. This statement is a generalization of the Kac lemma for classical Markov chains. [2].

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Title: Power spectral density of a single trajectory: Quantifying an ensemble by its random elements

Gleb Oshanin

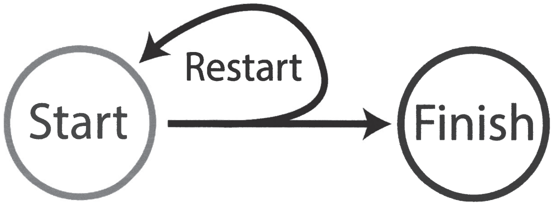
Sorbonne Université, CNRS

Abstract: Time-dependent processes are often analyzed using the power spectral density (PSD), which is calculated by making an appropriate Fourier transform of individual trajectories and finding the ensemble-averaged value. In some cases, however, one cannot create a statistical sample of a big enough size and hence it is of a great conceptual and practical importance to understand to which extent a relevant information can be gained from the PSD of a single trajectory, S(f,T). Here we focus on the behaviour of S(f,T), which is a random, realization-dependent variable, for a broad family of anomalous diffusion processes – the so-called fractional Brownian motion with Hurst-index H, and derive exactly its probability-density-function. We show that S(f,T) is proportional - up to a random numerical-factor with universal distribution which we determine - to the ensemble-averaged PSD. For subdiffusion (H<1/2) we find that S(f,T) ~ A/f^{2H+1} with random-amplitude A. In sharp contrast, for superdiffusion (H>1/2) S(f,T) ~ B T^{2H-1}/f^2 with random amplitude B. Remarkably, for H>1/2 the PSD exhibits the same frequency-dependence as Brownian motion, a deceptive property that may lead to false conclusions when interpreting experimental data. Notably for H>1/2 the PSD is ageing and it explicitly depends on the observation time T. Our predictions for both subdiffusion and superdiffusion are confirmed by experiments in live cells and in agarose hydrogels, and by extensive simulations.

First Passage Under Restart

A. Pal[1,2,3] and S. Reuveni[1,2,3]

[1]School of Chemistry, Tel-Aviv University, Israel.
[2]Center for the Physics and Chemistry of Living Systems, Tel Aviv University, Israel.
[3]The Sackler Center for Computational Molecular and Materials Science, Tel Aviv University, Israel.
E-mail: shlomire@tauex.tau.ac.il



Stopping a process in its midst—only to start it all over again—may prolong, leave unchanged, or even shorten the time taken for its completion. Among these three possibilities the latter is particularly interesting as it suggests that restart can be used to expedite the completion of complex processes involving strong elements of chance. This turned out to be important in computer science where restart drastically improves performance of randomized algorithms, but is not less relevant to many physical, chemical, and biological processes where restart plays a central role. We will develop a generic approach to first-passage under restart and use it to show that key features of diffusion under restart—the ultimate poster boy for this wide and diverse class of problems—are in fact completely universal. Time permits, we will also discuss how these findings are related to a series of surprising developments in our understanding of enzymatic catalysis at the single-molecule level.

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First-passage times of Markovian and non-Markovian random walks

Olivier Bénichou

CNRS, UPMC, Paris, France

Discrete-time quantum walks with neutral atoms in optical lattices

Manolo R. Lam[1], Gautam Ramola[1], Muhammad Sajid[1], Natalie Peter[1], Richard Winkelmann[1], Thorsten Groh[1], Carsten Robens[1], Wolfgang Alt[1], Dieter Meschede[1], János Asbóth[2], Antonio Negretti[3], Andrea Alberti[1]

alberti@iap.uni-bonn.de

[1] *Institut für Angewandte Physik, Wegelerstr. 8, 53115 Bonn, Germany*
[2] *Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O. Box 49, H-1525 Budapest, Hungary*
[3] *Zentrum für Optische Quantentechnologien, Luruper Chaussee 149, 22761 Hamburg, Germany*

I will report on experiments realizing discrete-time quantum walks of neutral cesium atoms in an optical-lattice potential: At each step of the walk, the individual atoms are moved by a discrete number of lattice sites in a direction depending on their electron spin orientation. Discrete transport operations are carried out in a short time (~10 μs) and with a high spatial precision (~1Å). For this purpose, we use polarization-synthesized optical lattices [1]—a novel implementation of state-dependent periodic potentials—which allow us to independently control the position (as well as the depth) of the two lattice potentials trapping $|\uparrow\rangle$ or $|\downarrow\rangle$ electron-spin states, respectively.

In a novel two-dimensional quantum-walk machine, we have recently demonstrated state-dependent transport of cesium atoms along the *x*- and *y*-axis. I will present our plans how to exploit the two dimensions to study quantum transport properties in periodically driven topological insulator materials.

Recently, we have been investigating applications of optimal control theory for the spin-dependent transport of atoms—the key component of our quantum-walk experiments—demonstrating that we can attain the quantum speed limit allowed by our optical-lattice system.

For the future, we envisage discrete-time quantum-walk experiments with many atoms that are initially prepared in the motional ground state of well-defined lattice sites [2]. This holds the promise to realize a BosonSampling machine with a large number of indistinguishable atoms, which can be scaled well above 50.

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The spectral dimension controls the decay of the quantum first detection probability

Felix Thiel[1], **David A. Kessler**[1] **and Eli Barkai**[1]

[1]*Bar-Ilan University, Dept. of Physics, 5290002 Ramat Gan, Israel*
E-mail: thiel@posteo.de

We consider a quantum system with a stationary Hamiltonian that is initially prepared in some state $|\psi_d\rangle$ and repeatedly projectively probed with a fixed period τ in this state. We ask for the probability that the system is detected in $|\psi_d\rangle$ for the very first time, F_n, where n is the number of detection attempts. We relate the asymptotic decay and oscillations of F_n with the system's energy spectrum, which is assumed to be absolutely continuous. In particular F_n is determined by the Hamiltonian's measurement spectral density of states (MSDOS) $f(E)$, that is closely related to the density of energy states (DOS). We find that F_n decays like a power law whose exponent is determined by the power law exponent d_S of $f(E)$ around its singularities E^*. Our findings are analogous to the classical first return theory of random walks. In contrast to the classical case, the decay of F_n is accompanied by oscillations with frequencies that are determined by the singularities E^*. This gives rise to critical detection periods τ_c at which the oscillations disappear. In the ordinary case d_S can be identified with the spectral dimension found in the DOS. Furthermore, the singularities E^* are the van Hove singularities of the DOS in this case. We find that the asymptotic statistics of F_n depend crucially on the initial and detection state and can be wildly different for out-of-the-ordinary states, which is in sharp contrast to the classical theory.

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Abstracts of Posters

(in alphabetical order)

Survival probability of random walkers in growing domains

F. Le Vot[1], C. Escudero[2], E. Abad[3], S.B. Yuste[1]

[1]*ICCAEx (Instituto de Computación Científica Avanzada, UEx), Badajoz, Spain*
[2] *ICMAT (Instituto de Ciencias Matemáticas, CSIC), Madrid, Spain*
[3] *ICCAEx (Instituto de Computación Científica Avanzada, UEx), Mérida, Spain*

Encounter-controlled processes in growing domains are relevant for many natural phenomena, notably in Biology and Cosmology. As a result of the effects induced by a sufficiently fast domain growth, the underlying first-passage properties can be dramatically altered (survival probabilities can e.g. be strongly increased). The implications are immediately clear for problems involving non-interacting walkers subject to the action of absorbing boundaries [1]. For this case, analytical results can be straightforwardly obtained in a wide variety of situations by switching to so-called comoving coordinates and to a suitably defined time scale. This double transformation in time and space then allows one to tackle the problem by taking advantage of the solution for the standard case of a static domain.

What is perhaps less obvious is that the above transformation can still be used to extract the main features of certain encounter-controlled reactions involving many interacting walkers. By way of example, we consider here the particular case of diffusion-controlled coalescence A+A->A in one spatial dimension [2]. As is well known, the kinetics of this many-body system can be reduced to a first-passage problem for a pair of neighboring particles (or, equivalently, to a first-passage problem for one of the two particles in the reference frame where its neighbor is at rest). Our results show that the time decay of the concentration in the case of a homogeneously, sufficiently fast growing 1d domain is very different from the case of a static domain. Decay to a non-empty steady state is possible, involving a strong memory of the initial condition. Besides, the fluctuation-dominated behavior observed in the case of a static domain may turn into a very different behavior for a sufficiently large domain growth rate. In this limit, the behavior is captured by the standard mean-field equation augmented with a dilution term arising from the deterministic domain growth. A similar conclusion holds for the closely related annihilation reaction A+A->0 [2,3], which is known to lie in the same universality class as the A+A->A system.

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Time-Multiplexed Photonic Quantum Walks with a 4-dimensional coin

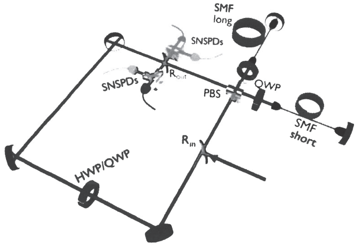
Sonja Barkhofen[1*], Lennart Lorz[1], Evan Meyer-Scott[1], Thomas Nitsche[1], Václav Potoček[2], Igor Jex[2], Christine Silberhorn[1]

[1]*Applied Physics, University of Paderborn, Warburger Strasse 100, 33098 Paderborn, Germany*

[2]*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 11519 Prague, Czech Republic*

**Sonja.Barkhofen@uni-paderborn.de*

Photonic quantum walk systems serve as a standard model to describe the dynamics of quantum particles in a discretized environment and act as a versatile simulator for complex quantum systems, which are not as readily accessible. However, their experimental realization requires setups with increasing complexity in terms of number of modes and control of the system parameters.



Setup scheme of a time-multiplexed quantum walk architecture based on a Michelson interferometer

Here, we present a photonic quantum walk on a looped Michelson interferometer and demonstrate the benefits of this new interferometric geometry. The time-multiplexing approach provides high homogeneity, precise control of the system parameters and optimal resource efficiency as was shown already for a Mach-Zehnder type setup [1–3]. By exploiting the two different travelling directions in the loop in addition to the two polarizations of the walker we implement a 4D coin space for a 1D walk. Fast electro-optic modulators realising dynamic coin operations enable us to study coupled quantum walks and revivals in finite 1D walks with periodic boundary conditions of programmable size paving the way towards quantum search applications.

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Scaled Brownian motion with resetting

A.S. Bodrova[1] , **A.V. Chechkin[2] and I.M. Sokolov[1]**

[1]Humboldt University, Department of Physics,12489 Berlin, Germany
[2]Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam, Germany

In the intermittent stochastic processes the dynamics of the system may be interrupted and recommenced at random times from the initial condition. Examples of such processes are found in many fields such as chemistry, biology, ecology and computer science. The time between resetting events may be distributed according to the exponential law or according to the power law. It may be shown that random resetting fundamentally changes the properties of the diffusion process. In the presence of resetting there is a competition between the tendency of diffusive spreading and confinement around the initial state. In our study during the resetting events the particle performs scaled Brownian motion: diffusive motion with time-dependent diffusion coefficient. We calculate mean-squared displacement and probability density function as main characteristics of this process.

Continuous-Time Quantum-Computing: Finding spin-glass ground-states using Quantum Walks

Adam Callison[1], Florian Mintert[1], Nicholas Chancellor[2] and Viv Kendon[2]

[1]Imperial College London, London, United Kingdom
[2]Durham University, Durham, United Kingdom

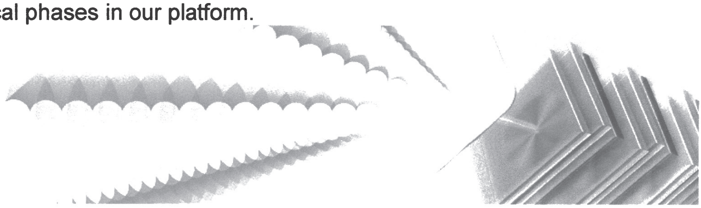
While a majority of the research in quantum computing is focused on the universal, discrete quantum logic of the gate model, there is scope for more specialized approaches to quantum computation that could have nearer term impact. Continuous time quantum computing (CTQC) is a paradigm in which computation is performed by continuous evolution with a Hamiltonian encoding a problem such that its ground-state represents the problem solution. We explore, in the context of quantum-simulator-like hardware, a quantum walk (QW) based strategy in which quantum interference and superposition lead to a QW that propagates (and hence solves problems) faster than its classical counterpart. We introduce the approach with the help of the unstructured-search problem (the subject of Grover's algorithm in the gate model). We then present a detailed numerical investigation of applying QWs to a realistic NP-hard problem: finding the ground-state of a Sherrington-Kirkpatrick spin-glass. We describe the fundamental difficulties of and necessary modifications to the application of QWs to these problems over and above the unstructured-search problem. Then, we present an estimate of the runtime-scaling, based on small instances, of this strategy. This estimate takes into account repetition (to amplify a success probability that scales down with system size) and an initial mixing-time. While additional work is needed, these preliminary results are suggestive of a runtime-scaling that is superior to some classical approaches.

Probing Topological phases in quantum walks with spatial modes of light

F. Cardano[1] , A. D'Errico[1], P. Massignan[2,3] ,A. Dauphin [2], M. Maffei[1,2] , V. Cataudella [1,4], G. De Filippis [1,4], B.Piccirillo[1] ,C. de Lisio[1], M. Lewenstein [2,3], L.Marrucci[1,5].

[1] Dipartimento di Fisica, Università di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, via Cintia, Napoli 80126, Italy;
[2] ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain;
[3] ICREA-Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain;
[4] CNR-SPIN, Complesso Universitario di Monte Sant'Angelo, Via Cintia, Napoli 80126, Italy;
[5] CNR-ISASI, Via Campi Flegrei 34, Pozzuoli (NA) 80078, Italy

Topological phases of matter have recieved widespread interest from fields like quantum computing, spintronics and metrology [6]. These phases are characterized by global topological order, which manifests in phenomena like robust edge states and quantized currents. Quantum walks have proven to be ideal platforms to investigate the fundamental features of topological phases [5]. Here we present a photonic quantum walk, employing spatial modes of light [1][2], which shows general features of one dimensional periodically driven systems with chiral symmetry [4]. Our platform encodes the coin space with the polarization and the walker space is associated to an infinite dimensional degree of freedom, e.g. the Orbital Angular Momentum. We introduce a new observable, the chiral displacement, that, in the long time limit, becomes equal to the topological invariant of the system [3]. Measuring this bulk property we are able to distinguish between the different topological phases in our platform.



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Benchmarking multi-walker interference in a quantum walk simulator

Aurél Gábris,[1,2] Thomas Nitsche,[3] Linda Sansoni,[3]
Sonja Barkhofen,[3] Igor Jex,[4] and Christine Silberhorn[3]

[1] *Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 115 19 Praha 1 – Staré Město, Czech Republic*

[2] *Department of Quantum Optics and Quantum Information, Wigner Research Centre for Physics, Budapest, Konkoly–Thege M. u. 29–33, H-1121 Budapest, Hungary*

[3] *Applied Physics, University of Paderborn, Warburger Straße 100, 33098 Paderborn, Germany*

[4] *Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 115 19 Praha 1-Staré Město, Czech Republic*

Discrete time quantum walks (DTQW) in the single walker regime are well-known to offer a quadratic speedup over classical random-walk based algorithms. Employing multiple walkers and their interactions in an algorithm is expected to allow us to attain the quantum advantage, i.e. exponential speedup over the classical approach [1]. We propose to employ a discrete analogon of the well-known Hong–Ou–Mandel (HOM) experiment [4] to test the ability of a 1D quantum walk setup to exploit genuine multi-partite quantum effects, an essential ingredient for attaining quantum advantage. We apply the discretisation to the HOM interference scenario where the initial photonic wave packets are separated in two orthogonal polarisations of the same spatial mode. While we rely on the terminology of optics, the results are general and can be applied to any DTQW platform.

We revisit the notion of coincidence within the discretised framework, distinguishing strict and loose coincidences. We show how these coincidences can expose the quantum statistics of the walkers, and present explicit procedures to benchmark the suitability of a given DTQW implementation to perform multi-walker protocols. The benchmark assumes the dynamical control of coin operators and the availability of two localised quantum walkers readily available in time-multiplexing setups [2, 3]. In particular, we analyse the probability of simultaneously detecting two walkers, respectively in $|L\rangle$ and $|R\rangle$ states, at the final step. The corresponding event is experimentally signalled by two appropriate detector clicks in coincidence. Just like in the case of the usual HOM experiment, if this probability as a function of the initial distance between the two walkers exhibits the well-known dip, we are assured that the genuine quantum nature of the walkers has been preserved during their manipulation in the apparatus.

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The topological classification of one-dimensional symmetric quantum walks

C. Cedzich[1], T. Geib[1], F. A. Grünbaum[2], C.Stahl[1], L.Velázquez[3], A. H. Werner[4,5], R. F. Werner[1]

[1] *Institut für Theoretische Physik, Leibniz Universität Hannover, Germany*
[2] *Department of Mathematics, University of California, Berkeley*
[3] *Departamento de Matemática Aplicada & IUMA, Universidad de Zaragoza, Spain*
[4] *QMATH, Department of Mathematical Sciences, University of Copenhagen, Denmark*
[5] *NBIA, Niels Bohr Institute, University of Copenhagen, Denmark*

We give a topological classification of quantum walks on an infinite 1D lattice, which obey one of the discrete symmetry groups of the tenfold way, have a gap around some eigenvalues at symmetry protected points, and satisfy a mild locality condition. No translation invariance is assumed. The classification is parameterized by three indices, taking values in a group, which is either trivial, the group of integers, or the group of integers modulo 2, depending on the type of symmetry. The classification is complete in the sense that two walks have the same indices if and only if they can be connected by a norm continuous path along which all the mentioned properties remain valid. Of the three indices, two are related to the asymptotic behaviour far to the right and far to the left, respectively. These are also stable under compact perturbations. The third index is sensitive to those compact perturbations which cannot be contracted to a trivial one. The results apply to the Hamiltonian case as well. In this case all compact perturbations can be contracted, so the third index is not defined. Our classification extends the one known in the translation invariant case, where the asymptotic right and left indices add up to zero, and the third one vanishes, leaving effectively only one independent index. When two translation invariant bulks with distinct indices are joined, the left and right asymptotic indices of the joined walk are thereby fixed, and there must be eigenvalues at 1 or −1 (bulk-boundary correspondence). Their location is governed by the third index. We also discuss how the theory applies to finite lattices, with suitable homogeneity assumptions.

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Impact of the malicious input data modification on the efficiency of quantum algorithms

A. Glos[1,2] and J. A. Miszczak[1]

[1]Institute of Theoretical and Applied Informatics, Polish Academy of Sciences, Bałtycka 5, 44-100 Gliwice, Poland
[2] Institute of Informatics, Silesian University of Technology, Akademicka 16, 44-100 Gliwice, Poland

Our main result is pointing the vulnerability of quantum algorithms to the complexity attacks. Our approach is based on the analysis of input data. As such it can be used to discover weaknesses of quantum computers resulting from the application of quantum algorithms on input data unsuitable for processing on quantum machines. This is in contrast to the common approach where only the theoretical computational complexity is taken into account.

We have developed the theoretical framework for quantifying the efficiency of the attacks. We have constructed an attack based on exceptional configurations and analysed it in the context of its applicability and efficiency. The analysis confirms that it is possible to decrease the efficiency of quantum spatial search based on Szegedy walk by malicious modification of input data.

One should note that the presented results can be applied for a general class of graphs. This is in contrast to the results from [2], where only special classes of graphs were considered. For those classes it can be shown analytically that the algorithm complexity changes from optimal quantum to classical.

The models of random graphs used for assessing the security of quantum algorithms mimic the structure of real-world data. As such the presented analysis confirms that the theoretical security of quantum procedures can be inadequate when the algorithms are applied for specific input data. This includes input data which encode the connections observed in complex networks.

The results base on paper accessible on arXiv [1].

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Biased continuous-time random walks for ordinary and equilibrium cases: facilitation of diffusion, ergodicity breaking and ageing

Ru Hou[1,2], **Andrey G. Cherstvy**[2], **Ralf Metzler**[2] **and Takuma Akimoto**[3]

[1]School of Mathematics and Statistics, Lanzhou University, Lanzhou 730000, China
[2] Institute for Physics & Astronomy, University of Potsdam, 14476 Potsdam, Germany
[3]Department of Physics, Tokyo University of Science, Noda, Chiba 278-8510, Japan

We examine renewal processes with power-law waiting time distributions (WTDs) and non-zero drift via computing analytically and by computer simulations their ensemble and time averaged spreading characteristics. All possible values of the scaling exponent α are considered for the WTD $\psi(t) \sim 1/t^{1+\alpha}$. We treat continuous-time random walks (CTRWs) with $0 < \alpha < 1$ for which the mean waiting time diverges, and investigate the behaviour of the process for both ordinary and equilibrium CTRWs for $1 < \alpha < 2$ and $\alpha > 2$. We demonstrate that in the presence of a drift CTRWs with $\alpha < 1$ are ageing and non-ergodic in the sense of the non-equivalence of their ensemble and time averaged displacement characteristics in the limit of lag times much shorter than the trajectory length. In the sense of the equivalence of ensemble and time averages, CTRW processes with $1 < \alpha < 2$ are ergodic for the equilibrium and non-ergodic for the ordinary situation. Lastly, CTRW renewal processes with $\alpha > 2$—both for the equilibrium and ordinary situation—are always ergodic. For the situations $1 < \alpha < 2$ and $\alpha > 2$ the variance of the diffusion process, however, depends on the initial ensemble. For biased CTRWs with $\alpha > 1$ we also investigate the behaviour of the ergodicity breaking parameter. In addition, we demonstrate that for biased CTRWs the Einstein relation is valid on the level of the ensemble and time averaged displacements, in the entire range of the WTD exponent α.

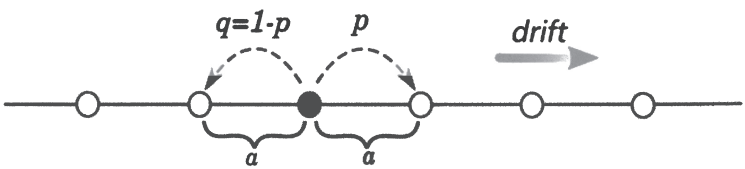


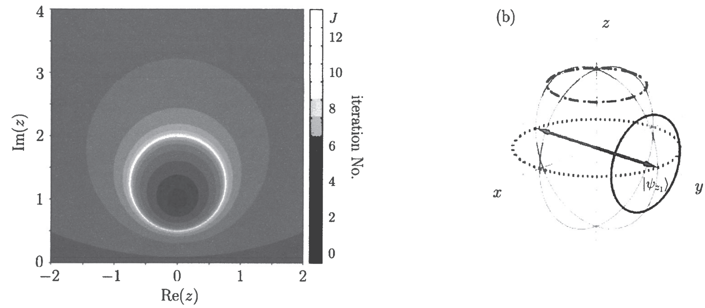
FIG. 1: Schematic representation of asymmetric particle jumps for biased CTRWs, with some parameters indicated.

Quantum state matching of qubits via measurement-induced nonlinear transformations

<u>O. Kálmán</u>[1] and T. Kiss[1]

[1]Institute for Solid State Physics and Optics, Wigner Research Centre, Hungarian Academy of Sciences, Budapest, Hungary

We consider the task of deciding whether an unknown qubit state falls in a prescribed neighborhood of a reference state. We assume that several copies of the unknown state are given and apply a unitary operation pairwise on them combined with a postselection scheme conditioned on the measurement result obtained on one of the qubits of the pair. The resulting transformation is a deterministic, nonlinear map in the Hilbert space. We derive a class of these transformations capable of orthogonalizing nonorthogonal qubit states after a few iterations [1]. These nonlinear maps orthogonalize states which correspond to the two different convergence regions of the nonlinear map. Based on the analysis of the border (the so-called Julia set) between the two regions of convergence, we show that it is always possible to find a map capable of deciding whether an unknown state is within a neighborhood of fixed radius around a desired quantum state. We analyze which one- and two-qubit operations would physically realize the scheme. It is possible to find a single two-qubit unitary gate for each map or, alternatively, a universal special two-qubit gate together with single-qubit gates in order to carry out the task [2].



(left figure) Number of iterations needed to reach the reference state (inside the yellow circle) or its orthogonal pair (outside region) in the quantum state matching protocol. (right figure) The decomposition of the nonlinear map of the quantum state matching protocol (shown on the Bloch sphere).

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Asymptotics of random density matrices

M. Kornyik[1]

[1] *Wigner Research Centre for Physics, Budapest, Hungary and Eötvös Loránd University, Budapest, Hungary*

The pure states of a quantum system can be identified with the set of rays of a Hilbert space, which also coincides with the surface of its unit ball. In finite dimensions this ball is a compact set, hence one can define a canonical probability measure (the uniform distribution) on it representing a randomly chosen pure state. Although if the observed system is in a mixed state, rays are not enough to describe the state of the system, and so-called density matrices have to be introduced. The set of these objects is not compact, therefore there is no canonical way to define a probability measure. Two types of measures are considered mainly: those generated by some metric (i.e. Bures distance $d(\rho, \sigma) = 2 \arccos(\rho^{1/2} \sigma \rho^{1/2})$), and those induced by partially tracing a random pure state of a larger system. It can be shown that random density matrices having distribution of the second kind can be written as $XX^\dagger / \mathrm{Tr}(XX^\dagger)$, where X is a $p \times n$ random matrix. Since the spectral asymptotics of matrices of the type $XX^\dagger$ is well known under quite general conditions it makes sense to study random density matrices of the previously mentioned type.

We will show that the spectral asymptotics of these matrices coincide with that of sample covariance matrices under proper normalization. As an application we will also show that the von Neumann entropy of these matrices grows logarithmically and exhibits a Strong Law of Large Numbers type of behavior in the limit.

These results are based on [1], and are generalizations of those of Nechita, and Życkowski and Sommers.

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Anomalous Diffusion on the Surface of Mammalian Cells

S. Sadegh[1], L. Solé[2], M. Metz[2], G. Sikora[1,3], K. Burnecki[3], A. Wyłomańska[3], A. Weron[3], S. Hentges[2], M.M. Tamkun[2] and D. Krapf[1]

[1] Electrical & Computer Engr., Colorado State University, Fort Collins, Colorado, USA
[2] Biomedical Sciences, Colorado State University, Fort Collins, Colorado, USA
[3] Hugo Steinhaus Center, Wrocław Univ. of Science and Technol., Wrocław, Poland

Tracking individual proteins on the surface of live mammalian cells reveals complex dynamics involving anomalous diffusion and clustering into nanoscale domains. Theoretical models indicate that anomalous diffusion can be caused by vastly different processes. By performing time series and ensemble analysis of extensive single-molecule tracking in combination with stochastic modeling, we show that most trajectories violate the ergodic hypothesis, one of the cornerstones of statistical physics. In particular, ergodicity breaking manifests as substantial differences between the time-averaged and the ensemble-averaged observables. We find that ergodicity breaking is caused by the transient localization of membrane proteins within nanoscale domains, such as endocytic pits. Furthermore, using a combination of dynamic super-resolution imaging and single-particle tracking, we observe that the actin cytoskeleton introduces barriers leading to the compartmentalization of the plasma membrane and that proteins are transiently confined within actin domains. Our results show that the actin-induced compartments are scale free and that the actin cortex forms a self-similar fractal structure.

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Reachability of Random Walkers on Scale-Free Networks

Aanjaneya Kumar[1], **Yagyik Goswami**[2] **and M.S. Santhanam**[1]

[1] *Indian Institute of Science Education and Research, Pune, India*
[2] *Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India*

First occurrence events are ubiquitous in nature. The present work examines the first occurrence events in the context of random walks on complex networks by considering the distinct sites visited by multiple walkers. Random walks on discrete lattices are a fundamental model in physics that forms the basis for our understanding of transport and diffusion processes. We study the dynamics of W random walkers on a scale-free network with N vertices in terms of the fraction of distinct sites not visited by any of the walkers until time step t, known as unreachability. I will present results on how unreachability changes with time t and also how it scales with the number of walkers W. Finally, I will comment about the robustness of our results and discuss future work.

Efficient search with Lévy walks emerges from stochastic optimization

Ł. Kuśmierz[1], A. Goudarzi[1], T. Toyoizumi[1]

[1]RIKEN Center for Brain Science, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

A growing body of evidence shows that many organisms commonly exhibit Lévy walks (LWs) during their search behavior. Although there are multiple putative explanations as to why LWs might emerge from case specific search constraints, a general theory explaining this behavior is lacking. We show that Newton's optimization method with noisy measurements generically leads to heavy tails of the step-size distribution. The resulting stochastic process is a LW process with the tail index $\alpha = 1$. Since search patterns of many organisms are of this kind, our results suggest that they may be employing second order derivatives. Additionally, the magnitude of large jumps in our model strongly depends on the local curvature of the optimized function, with rarer jumps close to targets. This suggests that noisy Newton's optimization method may be an efficient way of combining global random exploration with locally optimal exploitation. We thus examine the circumstances under which the heavy-tailed steps can be advantageous for the search. We further discuss implications of our results for models of learning.

Anderson Localization of Two Interacting Particles Using Discrete-Time Quantum Walks

Merab Malishava[1,2], **Ihor Vakulchyk**[1,2], **Mikhail V. Fistul**[1], **and Sergej Flach**[1]

[1]Center for Theoretical Physics of Complex Systems, Institute for Basic Science (IBS), Daejeon 34051, South Korea.
[2]Basic Science Program, Korea University of Science and Technology (UST), Daejeon 34113, Republic of Korea.

We study Anderson localization in a system of two interacting particles (TIP) whose unitary evolution is efficiently emulated with Interacting Discrete-Time Quantum Walks (IDTQW). In a recent work [1] a single particle DTQW with disorder was studied. We use these results and compute the dependence of the size of the TIP wave function on the control parameters of the system. We are in particular interested in the scaling of the TIP localization length with the single particle localization length in the limit of large values of the latter. Two qualitatively different limits have been identified and will be addressed. Due to the efficiency of the unitary IDTQW we will enter scaling regions which were inaccessible by previous Hamiltonian TIP dynamics.

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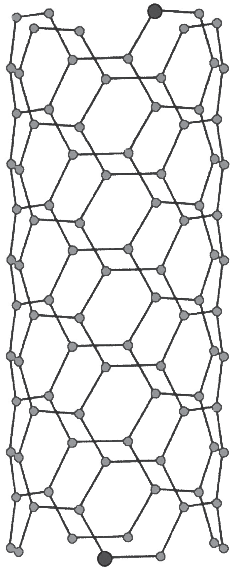
Asymptotic trapping in disrupted quantum walks on carbon nanotube structures

J. Mareš[1], **J. Novotný**[1] **and I. Jex**[1]

[1]*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*

We use the model of quantum walks to study a source-to-sink transport on carbon nanotube structures subjected to random dynamical disturbances. Despite a partial decoherence, an interference phenomenon can still be present where the walker remains trapped in the graph never reaching the sink.



While this trapping effect was already reported for a walk on a line graph [1], we present novel tools, both analytical and numerical, allowing for investigation of such complex structures as carbon nanotubes.

Our analytical methods allow to obtain the asymptotic trapping probability for lots of initial states, which is essential since the results for different initial states can range from full transfer to complete trapping. Further, the analytical insights allow us to understand phenomena as counter intuitive as that in some cases, the trapping probability decreases with the length of the tube.

When considering a numerical simulation, note that for example the graph shown here has 136 edges resulting in 2^{136} possible configurations of open/closed edges with corresponding evolution operators – a situation certainly not treatable by some brute-force methods.

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Evading Detection: The S_∞ Problem

D. Meidan and D.A. Kessler

Department of Physics & BINA, Bar-Ilan University, Ramat-Gan, Israel

Even after decades of research, the problem of first passage time statistics for quantum dynamics remains a challenging topic of fundamental and practical importance. Using a projective measurement approach, with a repetitive sampling time τ. We study the probability of first detection at the n^{th} attempt (F_n), using our previously obtained formula for the generating function of the distribution. In a previous article [1] we found some results for S_∞ (the probability of evading detection forever) and $\langle n \rangle$ for specific cases such as a ring and an infinite line. Our goal here is to find a generalized formula for S_∞ and compare to the previously obtained results for a ring. In addition, we also studied the case of a ring with a magnetic field, which breaks the *k*→-*k* symmetry, and the implications for S_∞ and F_n.

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First exit time distribution for diffusion on an interval with multiple semi-permeable barriers

N. Moutal[1] **and D. Grebenkov**[1]

[1]*PMC, CNRS - Ecole Polytechnique, F-91128 Palaiseau, France*

We present an efficient method to compute the eigenmodes and eigenvalues of the Laplace operator on an interval segmented by multiple semi-permeable barriers. This method allows us to compute the first exit time distribution analytically for regular arrangements of barriers and numerically for arbitrary ones. In particular, we derive a scaling law for this distribution in terms of the barriers permeabilities and spacings, which shows good numerical agreement even for a moderate number of barriers (more than 5). In the limit of quasi-impermeable barriers, the system becomes equivalent to a discrete random walk and we recover the corresponding classical results.

First Passage Under Restart

A. Pal and S. Reuveni

School of Chemistry, Tel Aviv University, Tel Aviv, Israel

First passage under restart has recently emerged as a conceptual framework suitable for the description of a wide range of phenomena, but the endless variety of ways in which restart mechanisms and first passage processes mix and match hindered the identification of unifying principles and general truths. Hope that these exist came from a recently discovered universality displayed by processes under optimal, constant rate, restart - but extensions and generalizations proved challenging as they marry arbitrarily complex processes and restart mechanisms. To address this challenge, we develop a generic approach to first passage under restart. Key features of diffusion under restart - the ultimate poster boy for this wide and diverse class of problems - are then shown to be completely universal.

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Systematic comparison of the search properties of Lévy walks and Lévy flights

V.V. Palyulin[1], A.V. Chechkin[1], R. Klages[2], R. Metzler[1]

[1] *Institute for Physics & Astronomy, University of Potsdam, D-14476 Potsdam-Golm, Germany*

[2] *Queen Mary University of London, School of Mathematical Sciences, Mile End Road, London E1 4NS, UK*

The famous Lévy flight foraging hypothesis (LFFH) is based on an idea that the scale-free Lévy motion represents the most successful strategy for foraging and blind target search. Since its appearance the hypothesis was discussed widely in the literature with both arguments for and against it [1]. Nevertheless, only a detailed study of the search performance by Lévy motions could provide a proper understanding of an extent to which LFFH works [2,3]. There are two different processes which result in Lévy motion, Lévy flights (LFs) and Lévy walks (LWs) [4]. These two random processes have identical scale-free distribution of relocation lengths. However, in the case of LWs the relocation lengths and times are coupled while for LFs both distributions are independent of each other. That results in rather different outcomes. For example, the mean-squared displacement diverges for LFs, but adopts finite values for LWs. In this contribution we compare the search properties of Lévy flights and Lévy walks for the case of blind search for a point-like target by considering the first arrival and the first passage distributions.

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Quantum computation with trotterized fermionic linear optics

P. Pyshkin[1]

[1]*Institute for Solid State Physics and Optics, Wigner Research Centre, Hungarian Academy of Sciences, P.O. Box 49, H-1525, Budapest, Hungary*

Linear fermionic optics [1] is an intensively researched field as theoretically as experimentally. Linearitv means that Hamiltonian of the fermion system contains only second order terms: $a_k^\dagger a_n$, where $a_n^\dagger(a_n)$ is the fermion creation (annihilation) operator of cite (mode) n. One of the simplest linear fermionic system is a one-electron which has continuous quantum walks in complete graph. This setting with one vertex marked as a solution corresponds to the well-known Grover search problem [2]. However, physical realization of complete graph can be difficult. In our report we show the way of implementation such complete graph quantum walks by using linear chain with only nearest neighbor hopping. We propose to use beam-splitter like unitary transformation together with trotterization [3] to realize complete graph quantum walks in such a system. This transformation is realized by evolving via special Hamiltonian with complex tunneling amplitude between nearest neighbor cites, which in turn can be reached by using external magnetic field. We show the example of Grover search realization with N=4 database size. Even when Trotter number is equal to one, we achieve more than 0.6 probability to achieve right answer. This probability is going up to unity with the Trotter number is increasing.

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Stochastic thermodynamics of periodically driven systems: Fluctuation theorem for currents and unification of two classes

Somrita Ray and **Andre C. Barato**

Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden, Germany

We present a fluctuation theorem for the currents for periodically driven small-scale systems that implies a fluctuation dissipation relation, symmetry relations for Onsager coefficients, and further relations for nonlinear response coefficients. Our results are valid for both heat engines driven by temperature variations and molecular pumps driven by external stimuli, which were being analyzed separately in the literature so far.

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Single-Molecule Theory of Enzymatic Inhibition Predicts the Emergence of Inhibitor-Activator Duality

T. Robin, S. Reuveni and M. Urbakh

School of Chemistry, Tel-Aviv University, Tel-Aviv, Israel

Enzymatic reactions can be generally described as binding of a substrate molecule to an enzyme to form a complex which ultimately leads to the catalysis of the substrate to product and the unbinding of the complex to a product and an enzyme which is free to start another cycle. These reactions have been well described by the Michaelis-Menten model for more than a century now. However, when one only examines enzyme catalysis in the bulk, many details of the inner mechanisms can be averaged in to very few measurable parameters. New experimental practices have opened the door to observing the catalysis of single enzyme molecules. These experiments, among other things, disputed an underlying assumption of the Michaelis-Menten model that the catalysis of substrate to product can be described as a memoryless process. In this work, we build a model which does not assume memory-less processes to describe the steps on the way to enzymatic catalysis and look in to the implication of such model. In particular, we look at the non-trivial effect of increased unbinding rate between the substrate and the enzyme. Moreover, we expanded our model to include the interaction with inhibitors, and show what one might learn on the inner workings of the catalysis even in bulk experiments.

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Continuous-time quantum walks on graphs with dynamical noise

M. Cattaneo,[1] M. A. C. Rossi,[2] M. G. A. Paris,[1] S. Maniscalco[2]

[1]Quantum Technology Lab, Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, IT-20133, Milan, Italy

[2]QTF Centre of Excelence, Turku Centre for Quantum Physics, University of Turku, FI-20014 Turun Yliopisto, Finland

Continuous-time quantum walks (CTQWs) describe the free evolution of quantum particles on N-vertex graphs. They have been subject of intense studies, both theoretical and experimental, as they have proven useful for several applications, ranging from universal quantum computation, to search algorithms (e. g. Grover), quantum transport and state or energy transfer. Given their relevance in applications, a realistic description of the dynamics of quantum walkers should take into account those sources of noise and imperfections that might jeopardize the discrete lattice on which the CTQW occurs.

Here we address the effects of classical random telegraph noise (a typical source of noise in solid state quantum devices) affecting the nearest-neighbor hopping amplitudes on CTQWs on different graph topologies, and we also discuss the effectiveness of spatial search algorithms in the presence of such noise.

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Prevention of Side-Channel Attacks in Timebin-Entanglement Based QKD Protocols

A. Sauer[1] **and G. Alber**[1]

[1] *TU Darmstadt, Darmstadt, Germany*

Bell tests are a crucial part of many key distribution protocols in quantum cryptography. To prevent side-channel attacks, it is necessary to close all loopholes in these tests, which might be exploited by an adversary. We investigate schemes based on timebin-entanglement with respect to their vulnerability to the fair-sampling loophole and the impact of detector inefficiencies. We propose a modified experimental setup to overcome the arising limitations of Franson-type interferometers [1].

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Surface-assisted search dynamics of a reactant

Jaeoh Shin[1] and Anatoly. B. Kolomeisky[1,2]

[1]Department of Chemistry, Rice University, Houston, USA
[2] Center for the theoretical biological Physics, Rice University, Houston, USA

The process of a reactant search for a target located on a surface is ubiquitous in Nature, in particular in chemical and biological processes. We study theoretically the dynamics of a reactant search for a small target on a two-dimensional surface from the bulk both in a continuum and discrete model. We find that depending on the scanning length λ of the reactant on the surface, which is determined by the reactant-surface interactions, the search dynamics are different: (i) for small λ, the reactant find the target via 3D bulk diffusion, (ii) for large λ, the reactant find the target via 2D surface diffusion, and (iii) for the intermediate λ, the reactant find the target via a combination of 3D and 2D diffusion which can minimize the search time T. The search times T in the continuum and discrete model are close, but not the same even we take the model parameters equivalently. We discuss the reasons for the discrepancy. Additionally, we investigate the dependence of the search time on the surface size and the position of the target. Finally, we discuss the relevance of our results with some recent experiments.

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Hopping in quasi-fractal superlattices of graphene quantum dots

Renat T. Sibatov
Ulyanovsk State University, Russia

Among graphene nanostructures, graphene ribbons and graphene quantum dots (graphQD) are of particular interest [1]. In 2011, Joung et al. [2] have shown that the low temperature electron transport properties of chemically functionalized graphene can be explained as sequential tunneling of charges through a 2D array of graphQDs and resistance data exhibit an Efros-Shklovskii variable range hopping arising from structural and size induced disorder.

In this work, we study diffusion regimes and recombination rates of charge carriers in artificial quasi-fractal graphQD superlattices forming Sierpinski's triangle and hexagonal carpet. Based on the density of states $D(E)$ for individual one-layer graphQDs of triangle and hexagonal shape optimized in a fractal superlattice, we estimate wave function localization radius a and hopping rates between neighboring graphQDs in arrays. Using tight-binding model and Miller-Abrahams relations for hopping rates [3] we perform Monte Carlo simulation of charge carrier hopping in artificial quasi-1d and 2d disordered arrays of graphQDs. The variations of the anomalous advection-diffusion parameters as functions of localization radius, temperature, electric field intensity, levels of energetic and structural disorder are studied. The model clarifies physical framework for diffusion and drift in fractal mesoscopic systems.

This work is partially supported by Russian-Chinese (RFBR & NSFC) grant 18-51-53018.

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Diffusing diffusivity VS generalised grey Brownian motion. Two models for diffusion in complex environments.

V. Sposini[1,2], A. V. Chechkin[1], F. Seno[4], G. Pagnini[2,3] and R. Metzler[1]

[1] Institute for Physics & Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany

[2] Basque Center for Applied Mathematics, 48009 Bilbao, Spain

[3] Ikerbasque - Basque Foundation for Science, Bilbao, Spain

[4] INFN, Padova Section and Department of Physics and Astronomy "Galileo Galilei", University of Padova, 35131 Padova, Italy

A considerable number of systems have recently been reported in which Brownian yet non-Gaussian dynamics was observed[1]. These are processes characterised by a linear growth in time of the mean squared displacement, yet the probability density function of the particle displacement is distinctly non-Gaussian, and often of exponential (Laplace) shape. This apparently ubiquitous behaviour observed in very different physical systems has been interpreted as resulting from diffusion in inhomogeneous environments and mathematically represented through a variable, stochastic diffusion coefficient. Indeed different models describing a fluctuating diffusivity have been studied. Here we present a new view of the stochastic basis describing time dependent random diffusivities within a broad spectrum of distributions. In particular our study is based on the very generic class of the generalised Gamma distribution. Two models for the particle spreading in such random diffusivity settings are studied. The first belongs to the class of generalised grey Brownian motion[2] while the second follows from the idea of diffusing diffusivities[3]. The two processes exhibit significant characteristics which reproduce experimental results from different biological and physical systems. We emphasize that even when the non-Gaussian character appears for certain regimes only and in the tails of the distributions (thus with low probability), it may be essential for understanding the physics of many soft-matters systems in which rare events dominate first-passage processes. Thus, we promote these two physical models for the description of stochastic particle motion in complex environments[4,5].

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Anomalous metapopulation dynamics on scale-free networks

S. Fedotov[1] and H. Stage[1]

[1]*School of Mathematics, The University of Manchester, Oxford Road, M13 9PL, Manchester, United Kingdom*

We model transport of individuals across a heterogeneous scale-free network where a few weakly connected nodes exhibit heavy-tailed residence times. Using the empirical law Axiom of Cumulative Inertia and fractional analysis we show that `anomalous cumulative inertia' overpowers highly connected nodes in attracting network individuals. This fundamentally challenges the classical result that individuals tend to accumulate in high-order nodes. The derived residence time distribution has a non-trivial U-shape which we encounter empirically across human residence and employment times.

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Quantum walks on the Manhattan lattice and the L-lattice

Aurél Gábris[1], Igor Jex[2], Adrian Ortega[3], Martin Štefaňák[2] and Tereza Štefková[2]

[1] Wigner Research Center for Physics, Budapest, Hungary
[2] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[3] Institute of Physical Sciences, National Autonomous University of Mexico, Mexico City, Mexico

We address the problem of two-dimensional quantum walks on directed square lattices. We focus on two special cases, namely the Manhattan lattice [1] and the L-lattice [2]. These lattices share the property that at each of the nodes there are two incoming and two outgoing edges.
For homogeneous quantum walks on the Manhattan lattice it is shown that they can be viewed as quantum walks on undirected square lattice driven by four-dimensional coin satisfying certain restricting conditions. On the other hand, we show that homogeneous quantum walks on the L-lattice are equivalent to the so-called alternate two-dimensional quantum walks [3] which utilize only a two-dimensional coin.
Finally, we focus on the effect of trapping in the above discussed quantum walks, i.e. we analyze conditions under which the evolution operator of the walk has non-empty point spectrum. It is shown that for both models the trapping effect occurs only in certain trivial cases where the evolution operator lacks continuous spectrum and the walk does not spread.

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Scaling limits of Lévy walks with random rests

M.Teuerle

Faculty of Pure and Applied Mathematics,
Hugo Steinhaus Center,
Wroclaw University of Science and Technology,
Wroclaw, Poland
E-mail: marek.teuerle@pwr.edu.pl

In this work we continue investigation of asymptotic properties of different generalizations of Levy walk process, which is a remarkable example of coupled continuous-time random walk. [1-4]. Here we derive the scaling limit process and the asymptotic properties of a Levy walk with rest [2]. The exact model considered in our work is a coupled continuous-time random walk with jumps and waiting times being the same (up to a random variable indicating the direction of jump). Moreover, between pairs of jump and waiting time we have an additional random waiting time, which we call a rest. Depending on the distribution of the rests and their dependence with original waiting times we derive a scaling limit processes. We also comment on some properties of the scaling limits.

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Anderson localization in generalized discrete time quantum walks

I. Vakulchyk[1,2], M. V. Fistul[1,3], P. Qin[1] and S. Flach[1]
[1] *Center for Theoretical Physics of Complex Systems, Institute for Basic Science (IBS), Daejeon 34051, Republic of Korea*
[2] *Basic Science Program, Korea University of Science and Technology (UST), Daejeon 34113, Republic of Korea*
[3] *Russian Quantum Center, National University of Science and Technology "MISIS", 119049 Moscow, Russia*

We study Anderson localization in a generalized discrete time quantum walk — a unitary map related to a Floquet driven quantum lattice. It is controlled by a quantum coin matrix which depends on four angles with the meaning of potential and kinetic energy, and external and internal synthetic flux. Such quantum coins can be engineered with microwave pulses in qubit chains. The ordered case yields a two-band eigenvalue structure on the unit circle which becomes completely flat in the limit of vanishing kinetic energy. Disorder in the external magnetic field does not impact localization. Disorder in all the remaining angles yields Anderson localization. In particular, kinetic energy disorder leads to logarithmic divergence of the localization length at spectral symmetry points. Strong disorder in potential and internal magnetic field energies allows to obtain analytical expressions for spectrally independent localization length which is highly useful for various applications.

Experimental investigation of quantum witness and Leggett-Garg inequality

Kunkun Wang[1,2], Xiang Zhan[1,2], Zhihao Bian[1,2], Mengyan Xu[1,2], Lei Xiao[1,2], and Peng Xue[1,2,3]

[1] *Department of Physics, Southeast University, Nanjing 211189, China*
[2] *Beijing Computational Science Research Center, Beijing 100084, China*
[3] *State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China*

Since the birth of quantum mechanics, it has been difficult to reconcile the principle of quantum superposition with the intuitive experience of macroscopic objects, which appear to always inhabit explicit states independent of observation. Leggett and Garg formulated a possible solution by defining macroscopic realism (MR), posits that a macroscopic system will exist in a well-defined state at all times, and that this state can be measured without disturbing it (the assumption of noninvasive measurability). From these assumptions follow the Leggett-Garg inequalities (LGIs). Alongside such experimental investigations are likely to suffer from (i) stringent experimental requirements, (ii) marginal statistical significance, and (iii) logical loopholes. We address all of these problems by refining two tests of macroscopic realism, or "quantum witnesses", and implementing them in a microscopic test on a photonic qubit and qutrit. We also realize conventional Leggett-Garg tests on a three-level system and implement ideal negative measurements, which allow us to acquire information about the system (here, the photon) without interacting with it directly. In this way we obtain violations of three- and four-time Leggett-Garg inequalities that are significantly in excess of those obtainable in standard Leggett-Garg tests. At last, by using ambiguous measurements which do not reveal complete information about the state of the system and are non-repeatable, we construct a test of a Leggett-Garg inequality as well as tests of no-signaling-in-time for the measurements. We observe violations of the Leggett-Garg inequality that cannot be accounted for in terms of signaling. Moreover, we tailor the qutrit dynamics such that both ambiguous and unambiguous measurements are simultaneously nonsignaling.

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Generalized arcsine laws for fractional Brownian motion

Kay Wiese

ENS Paris, LPTENS, Paris, France

The three arcsine laws for Brownian motion are a cornerstone of extreme-value statistics. For a Brownian B(t) starting from the origin, and evolving during time T, one considers the following three observables: (i) the duration t_+ the process is positive, (ii) the time t_{last} the process last visits the origin, and (iii) the time t_{max} when it achieves its maximum (or minimum). All three observables have the same cumulative probability distribution expressed as an arcsine function, thus the name of arcsine laws. We show how these laws change for fractional Brownian motion X(t), a non-Markovian Gaussian process indexed by the Hurst exponent H. It generalizes standard Brownian motion (i.e. H=1/2). We obtain the three probabilities using a perturbative expansion in H-1/2. While all three probabilities are different, this distinction can only be made at second order in H-1/2. Our results are confirmed to high precision by extensive numerical simulations.

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Observation of topological edge states in parity-time-symmetric quantum walks

<u>Lei Xiao</u>[1,2], Xiang Zhan[1,2], Zhihao Bian[1,2], Kunkun Wang[1,2], Xingze Qiu[3], Barry C. Sanders[4], Wei Yi[3], Peng Xue[1,2]

[1] *Department of Physics, Southeast University, Nanjing 211189, China*
[2] *Beijing Computational Science Research Center, Beijing 100084, China*
[3] *Key Laboratory of Quantum Information, University of Science and Technology of China, CAS, Hefei 230026, China*
[4] *Institute for Quantum Science and Technology, University of Calgary, Alberta T2N 1N4, Canada*

Topological matter exhibits exotic properties yet phases characterized by large topological invariants are difficult to implement, despite rapid experimental progress. A promising route toward higher topological invariants is via engineered Floquet systems, particularly in photonics, where flexible control holds the potential of extending the study of conventional topological matter to novel regimes. We report the experimental detection of bulk topological invariants of two in non-unitary discrete-time quantum walks with single photons. The non-unitarity of the quantum dynamics is enforced by periodically performing partial measurements on the polarization of the walker photon, which effectively introduces loss to the dynamics. The topological invariant of the non-unitary quantum walk is manifested in the quantized average displacement of the walker, which is probed by monitoring the photon loss. We confirm the topological properties of the system by observing localized edge states at the boundary of regions with different topological invariants. We further demonstrate the robustness of both the topological properties and the measurement scheme of the topological invariants against disorder. Our work would stimulate further studies of topological phenomena in non-unitary quantum dynamics in a variety of physical systems.

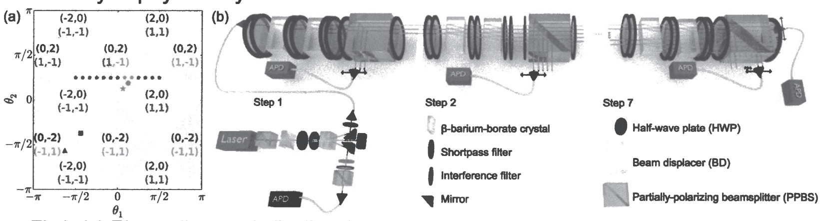

Fig1. (a) Phase diagram indicating the topological invariants. (b) Experimental setup.

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Quantum walks on a perturbed ring: The "return" problem

Ruoyu Yin, Eli Barkai

Department of Physics, Institute of Nanotechnology and Advanced Materials, Bar Ilan University, Ramat-Gan 52900, Israel

The "return" problem of quantum walks has been talked in details recently[1, 2], based on the quantum renewal equation derived in [1]. While in real experiments, it is almost impossible to build an ideal system without any "noise". So what we expect is to obtain the statistics of the return time of a quantum walker in a perturbed system, which we treat with adding a site energy. The model we are dealing with is a Bezene-type ring, whose energy levels are simple and degenerate in the absence of perturbation[1]. We will see that the site energy makes a difference to average return time as an example of symmetry breaking.

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