2024: Entropic Complexity Measures for Atomic Nuclei

(i) **Key words:** Complexity Science; Statistical Physics; Nuclear Physics;

(ii) **Thesis Supervisor and Contact person:** Jan Ryckebusch

(iii) **Research background**

Nuclei are prototypical examples of self-bound and strongly correlated quantum systems. Nuclear momentum distributions contain the information about the nuclear ground state in the momentum space. Below the Fermi momentum (about 25% of the nucleon's rest mass) nuclear momentum distributions are reminiscent for a strongly degenerate two-component (protons and neutrons) system of Fermions. Nuclear momentum distributions contain a fat high-momentum tail that can be connected with the physics of nuclei at small inter-nucleon distances in the most dense parts of the nucleus. The fat tails of the momentum distribution represent about 20% of the probability distribution and are responsible for a very large fraction of the average nuclear kinetic energy. The fat tails are expected to play an increasingly more important role as one faces exotic forms of dense nuclear matter as neutron stars (Ref: Article in Physics Today and arXiv:1905.13175). Over the last decade a technique to compute nuclear momentum distributions over the full momentum range has been developed in the research group Theoretical Nuclear Physics and Statistical Physics (arXiv:2106.01249 ; arXiv:1907.07259 ; arXiv:1808.09859).

(iv) **Research plan & research goals**

The major research goal of the MSc thesis is to numerically study the impact of the fat tails of the momentum distributions on the complexity of atomic nuclei. In order to quantify the complexity of atomic nuclei, use will be made of entropic measures such as the Shannon entropy and the entanglement entropy. We can build on some recent works that discuss entropic measures to quantify the complexity of atomic nuclei (https://arxiv.org/abs/2203.12079).

The milestones of the proposed study are: (i) a profound literature study of nuclear momentum distributions and measures that quantify the complexity (entropy) of atomic nuclei (ii) practical numerical implementation of entropic measures for the model for nuclear momentum distributions developed in our group; (iii) numerical study of the values of the entropic measures for various nuclei; (iv) identifying the major sources that determine the entropic measures for atomic nuclei (for example the impact of the neutron-to-proton content of nuclei).

2024: Entropic Complexity Measures for Assessing Volatile Markets

(i) **Key words:** Complexity Science; Econophysics; Stochastic processes; Statistical Physics;

(ii) **Thesis Supervisors and Contact persons:** Jan Ryckebusch, Stijn De Backer

(iii) **Research background**

Entropy is a measure of the disorder or randomness in a system, reflecting the system's level of uncertainty or information content. The concept of entropy is not uniquely relevant to thermodynamics and statistical mechanics, but can also be applied in the analysis of time series, in particular financial data. Despite the widespread popularity of the standard deviation as a measure of financial risk, its limitations become evident when confronted with extreme market events. Entropic complexity measures can be used to quantify market volatility and to characterize sudden economic events that can induce abrupt changes with potentially long-term consequences. A notable example is the impact of the COVID-19 pandemic. In conditions of extreme events, methodologies based on entropic principles can have their application in portfolio selection strategies and asset pricing problems.

References:

-Drzazga-Szczęśniak, Ewa A., et al. "*Entropy of financial time series due to the shock of war.*" Entropy 25.5 (2023): 823. (https://arxiv.org/abs/2303.16155)

-Rodriguez-Rodriguez, Noé, and Octavio Miramontes. "*Shannon Entropy: An econophysical approach to cryptocurrency portfolios.*" Entropy 24.11 (2022): 1583. (https://arxiv.org/abs/2210.02633)

-Sheraz, Muhammad, and Imran Nasir. "*Information-theoretic measures and modeling stock market Volatility: A Comparative Approach.*" Risks 9.5 (2021): 89. (https://www.mdpi.com/2227-9091/9/5/89)

(iv) **Research plan**

The milestones of the proposed study are:

(a) A profound literature study of entropic complexity measures and related topics, including Shannon/Tsallis/Rényi entropy, Kolmogorov complexity, etc.
(b) Developing methodologies to quantify information entropy in financial time series data, such as stock prices or market indices.
(c) The analysis of real-life financial data (available on e.g. Yahoo Finance); comparative analysis of the different entropic complexity measures.
(d) The conclusions may have their application in portfolio optimization strategies, asset pricing problems, and financial risk analysis.

2024: Quantum Walks and Its Extensions

(i) **Key words:** Stochastic Processes; Quantum Mechanics; Information Measures; Computational Physics;

(ii) **Thesis Supervisors and Contact persons:** Jan Ryckebusch, Stijn De Backer

(iii) **Research background**

The discrete-time quantum walk can be looked upon as the quantum counterpart of the classical random walk. It distinguishes itself from the classical random walk by the fact that the randomness does not arise from a stochastic transition between states, but from the inherent unpredictability of the outcome of a quantum measurement process. The time evolution in the quantum walk is characterized by a superposition of all possible trajectories, allowing for interference in successive time steps and for quantum correlations. In recent times, the quantum walk algorithm has been proposed as a promising tool to model the temporal evolution of financial assets.

The classical walk algorithm can be supplemented with additional features so as to better match the model with real-world situations (for example, through the addition of memory effects). Similarly, the quantum walk algorithm can be supplemented with additional features. This flexibility has been explored in literature, where numerous adaptations of the basic algorithm have been proposed, such as the inclusion of sequential aperiodic jumps and the elephant quantum walk which features memory effects. Advanced adaptations of the quantum walk can serve as a building block of more sophisticated quantum computation algorithms. Moreover, various methodologies to introduce decoherence effects (which cause a collapse to the classical case) into the quantum walk have been proposed.

References:

-Pires, Marcelo A., and SM Duarte Queirós. *"Quantum walks with sequential aperiodic jumps."* Physical Review E 102.1 (2020): 012104 (https://arxiv.org/abs/1910.02254)

-Di Molfetta, Giuseppe, Diogo O. Soares-Pinto, and Sílvio M. Duarte Queirós. *"Elephant quantum walk."* Physical Review A 97.6 (2018): 062112. (https://arxiv.org/abs/1709.09464)

-Kendon, Viv. *"Decoherence in quantum walks–a review."* Mathematical structures in computer science 17.6 (2007): 1169-1220. (https://arxiv.org/abs/quant-ph/0606016)

-Stijn De Backer, Luis E. C. Rocha, Jan Ryckebusch, Koen Schoors. *"On the potential of quantum walks for modeling financial return distributions"* (https://arxiv.org/abs/2403.19502)

(iv) **Research plan**

The milestones of the proposed study are:

(i) A profound literature study of the quantum walk and its extensions (including decoherence effects, the elephant quantum walk, quantum walks with jumps, etc.).

(ii) The practical implementation of the different algorithms for a variety of situations (e.g. on different graph topologies).

(iii) A comparative study of the probability distributions resulting from the different methodologies in terms of statistical properties and entropic complexity measures.

(iv) Designing novel adaptations of the quantum walk algorithm and analyzing their properties.