Quantum-like Modelling for AI and DM

Department of Solid State Engineering (KIPL FJFI ČVUT) & Department of Adaptive Systems (AS ÚTIA AV ČR)
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About our group

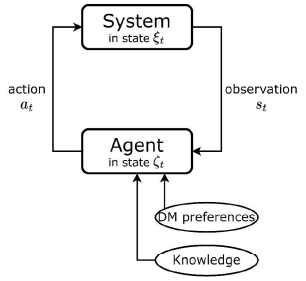
We are a small group of researchers and students bridging the Department of Solid State Engineering (Katedra inženýrství pevných látek, **KIPL**) and the Department of Adaptive Systems (Oddělení adpativních systémů, Ústav teorie informace a automatizace, **AS**). KIPL has a strong background in solid–state physics, nanostructures and the broad spectrum of emerging quantum technologies. AS builds on many years of experience in Bayesian learning, control theory and probabilistic decision making under uncertainty.
Our primary area of research is **quantum–like models for dynamic decision making under uncertainty**. We develop theoretic and algorithmic solutions and test them on (usually simulated) scenarios.

The omnipresent concept: Agent-System interaction loop

Consider **Agent** (decision-maker) which interacts with **System**, i. e. the part of the world Agent interested to influence/learn (expressed via Agent's decision-making (DM) aim or DM **preferences**).

- Agent receives **observations** informing about System's state and updates their internal **knowledge.**
- Based on their knowledge and preferences, Agent selects an **action** intended to influence System's future state.
- Agent's action directly affects System, causing its transition to a new state, which is then observed by Agent, and so for.
- **Objective:** to find an optimal **decision strategy** that guides Agent to achieve a desired DM aim despite **uncertainty.**
- **Static Decision Task (one-shot decision):** No time evolution, Agent selects only one action (e.g., choosing clothes).
- **Dynamic Decision Task:** Decision making evolves in time. At each time Agent selects optimal action based on observation.

The Closed Loop



Why quantum beyond the physics?

- Nowadays "quantum" become a buzzword like "machine learning" or "AI" was some time ago. The number of areas starting to do "quantum things" is growing every day. While many of them are meaningful, some are just blindly following the trends.
- Our strong reasons that quantum-like DM belong to the first category:

1. Quantum–like models proved to be effective to express *human* DM (to match real data).
2. Using quantum probability (non–commutative generalisation of Kolmogorov's probability) solves famous paradoxes (Allais, Ellsberg, Linda...).
3. We show that from a very general formalisation of the DM task, a probabilistic description follows from reasonable, fundamental assumptions. The appropriate general measure is quantum probability; classical probability appears as a special case.

Research direction 1: Towards quantum decision making

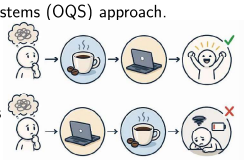
This direction builds on our work (Gaj, Kárný, 2024) leveraging quantum probability to solve cognitive paradoxes, directly comparing it to classical approaches. Pioneering researchers like J. Busemeyer and V. Yukalov have successfully demonstrated that Quantum Decision Theory (QDT) can resolve static behavioral paradoxes (like Allais paradox or Disjunction effect). However, real–world cognition is a dynamic process. We introduce a formal mathematical framework for modeling such dynamic DM tasks via a closed loop interaction of Agent and System, where quantum-like evolution was obtained as a byproduct. Any task of this type should be solved using quantum probability.

Challeges (possible BSc/MSc topics):

- **Testing and Comparison:** Formulate a sequential DM task, solve it via the proposed theory and compare the results with existing solutions.
- **Links to Open Quantum System approach:** Establish formal connections between the closed-loop dynamic DM formalism and Open Quantum Systems (OQS) approach.

References: (general ones)

- Gaj & Kárný (2024), doi:10.5281/zenodo.15250012
- Khrennikov (2023), ISBN:9783031290237 ...and others



Research direction 2: Quantum–like rat in a maze

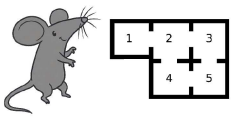
We illustrate quantum-like decision making on the macro scale with a toy: a rat navigating a 5-room maze using a quantum DM algorithm. The rat's movement is given by quantum DM algorithm.

Challenges (possible BSc/MSc topics):

- **Physics-informed Bayesian Learning:** Given exact past positions of the rat predict the rat's next position.
- **Quantum Control Theory:** Optimally steer the rat's by moving the "cheese" (adjusting the Hamiltonian attractors).
- **Multi–Agent Setup:** Scale the maze to multiple rats to study *entangled* behavioral routing and interaction effects.
- **Variational Quantum Algorithms:** Use VQCs to learn/predict the rat's behavior from limited observation data and compare generalisation with classical machine learning approaches or Bayesian learning.

References: (general ones)

- Gaj & Kárný (2025), doi:10.5281/zenodo.18651515
- Khrennikov (2023), ISBN:9783031290237 ...and others



What to expect?

- **Task assignment:** We support well-established tradition of **formulating the topic of bachelor/master diploma according to the student's preferences**, hobbies and skills. We don't do "standardised" tasks: every thesis is formulated as a novel piece of complex mosaic that our group is working on. The final BSc/MSc task is formulated during several meetings with the supervisor.
- **Theory vs. practice:** Projects can be theory-oriented (math and concepts) or implementation-focused (coding and experiments) and are adjusted to the student's preferences.
- **Prerequisites:** *depends on specific task* – usually basics of probability theory, linear algebra, quantum mechanics and programming. If you are coming from different field or you don't feel confident in some area, we will work on that together.
- **Time management:** While we highly value skillful and talented people, we prefer motivated students to the inconsistent ones. We require regular meetings and a consistent work during the term.

Contact us!

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