Towards Quantum Technologies in Quantum Resources Group

A. de Oliveira Junior, O. Reardon-Smith, R. Salazar, F. Shahbeigi, Kamil Korzekwa

Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 30-348 Krakow, Poland

JAGIELLONIAN UNIVERSITY IN KRAKÓW

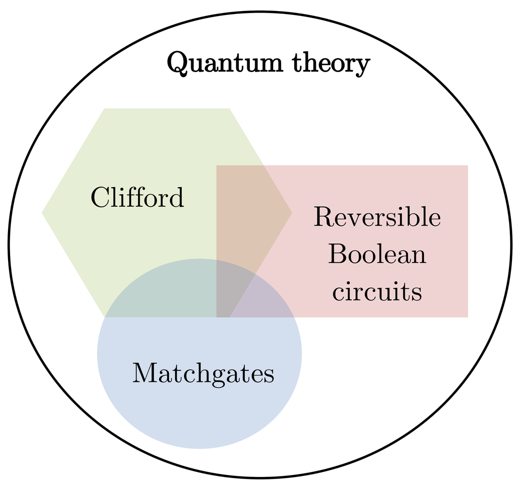
FNP Foundation for Polish Science TEAM-NET

Our goal is to develop a theoretical framework underpinning quantum technologies by identifying, characterising and proposing implementations of quantum resources.

Quantum Computing

Project: Fast estimation of outcome probabilities for quantum circuits

Goal: To develop a scheme for classical simulation of universal quantum circuits composed of Clifford and T gates.

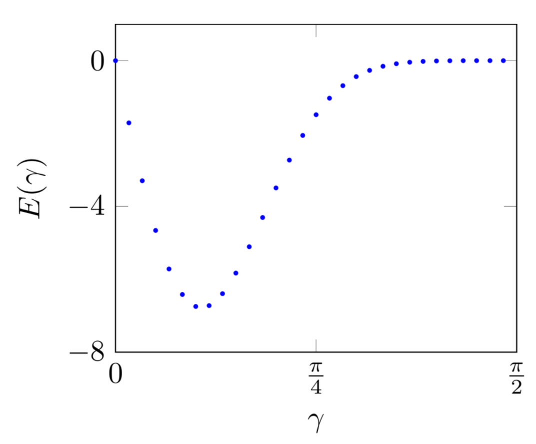


Quantum theory and some of its efficiently classically simulable subtheories

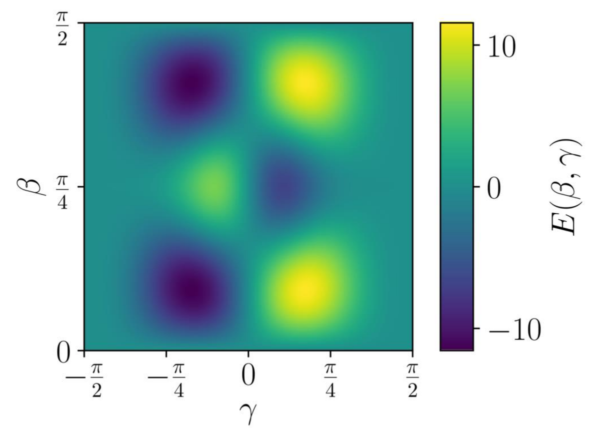
Simulation idea:

- "Break out" of the Clifford subtheory using gadgetization of T gates.
- Decompose gadgetizing states as sums of exponentially many states from the simulable subtheory.
- Use Monte Carlo sampling to estimate value of exponentially large sums.
- Classical cost of simulation scales as efficiently as possible – simulation cost proportional to the amount of quantum resources in the circuit.

Results: State-of-the-art classical simulation algorithm that permits practical simulation run-times for quantum circuits in previously inaccessible parameter regimes.



This curve shows how the energy of a state in a Quantum Approximate Optimization Algorithm (QAOA) procedure varies with one of the parameters. Our algorithms produced this diagram in 2 seconds, while the prior state of the art required "less than 3 days".



Our algorithms are so efficient we can compute QAOA energies for large numbers of points beyond the reach prior methods.

PRX Quantum X **3**, 020361 (2022) | Part of IBM Qiskit package | Algorithm: github.com/or1426

Project: Improved simulation of quantum circuits dominated by free Fermionic operations

Goal: To develop a scheme for classical simulation of universal quantum circuits composed of matchgates and SWAP gates.

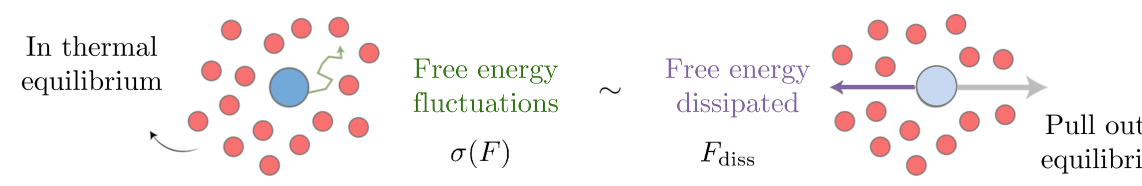
Results: Designed the desired simulation algorithm (details awaiting patent protection).

Ongoing patent application

Quantum Thermodynamics

Project: Fluctuation-dissipation relation for thermodynamic distillation processes

Goal: To find ways of minimizing free energy dissipation by employing quantum coherent effects.



Results: Explicit expressions and protocols for minimal amount of dissipated free energy for thermodynamic transformations of quantum systems:

$$F_{\rm diss} = A\sigma(F)$$

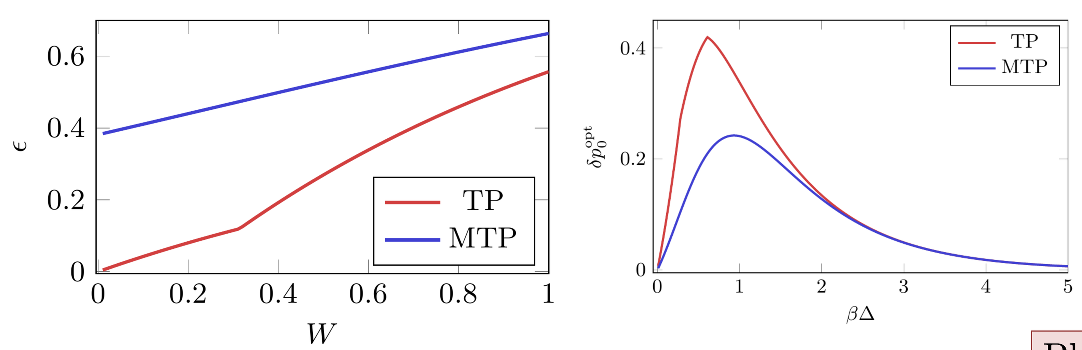
Can be reduced by preparing the system in coherent superposition of energy eigenstates!

Phys. Rev. E **105**, 054127 (2022)

Project: Optimizing thermalizations

Goal: To characterize the optimal use of thermodynamic resources under restrictions of limited control due to access only to transformations that could be easily implemented experimentally.

Results: Algorithmic method of finding optimal thermodynamic processes with limited control.



TP – ultimate thermodynamic bound
MTP – bound for limited control

Left: Optimal trade-off between the quality and amount of extracted work

Right: Optimal cooling power in one step of heat-bath algorithmic cooling protocol

Algorithm: github.com/KorzekwaKamil

Phys. Rev. A **106**, 012426(2022)
Phys. Rev. Lett. **129**, 040602 (2022)
Physics **15**, 110 (2022)

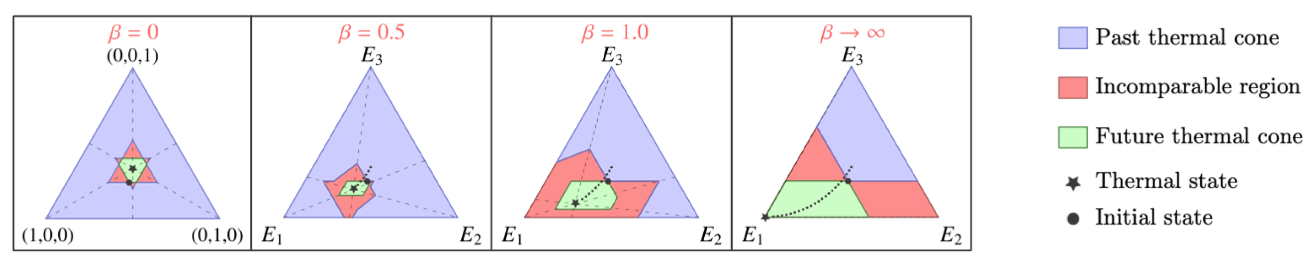
Project: Geometric structure of thermal cones

Algorithm: github.com/adeoliveirajunior

Goal: To understand the thermodynamic arrow of time through geometric methods

arXiv: 2207.92237

Results: Algorithmic construction of the thermodynamic past and future of a quantum state.

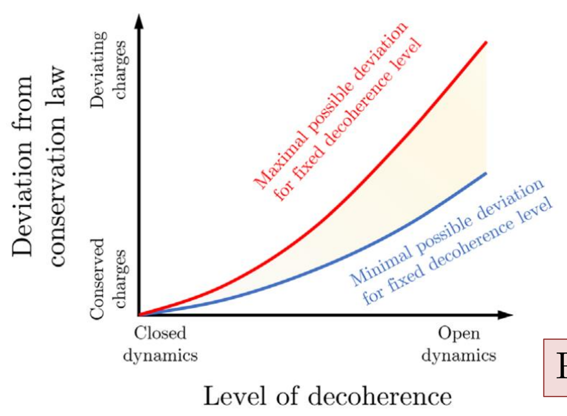


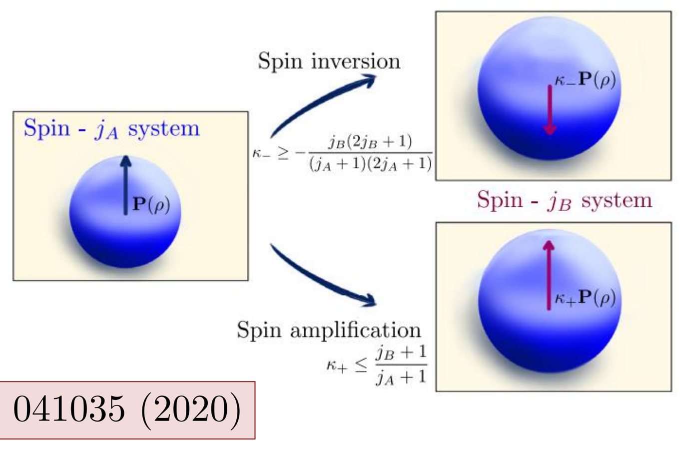
Quantum Control

Project: Robustness of Noether's principle

Goal: To understand to what degree does Noether's principle hold for open (non-isolated) quantum systems that possess a continuous symmetry.

Results: Trade-off relations between deviation from conservation laws and level of decoherence under symmetric dynamics; and the form of optimal spin inversion and amplification processes.



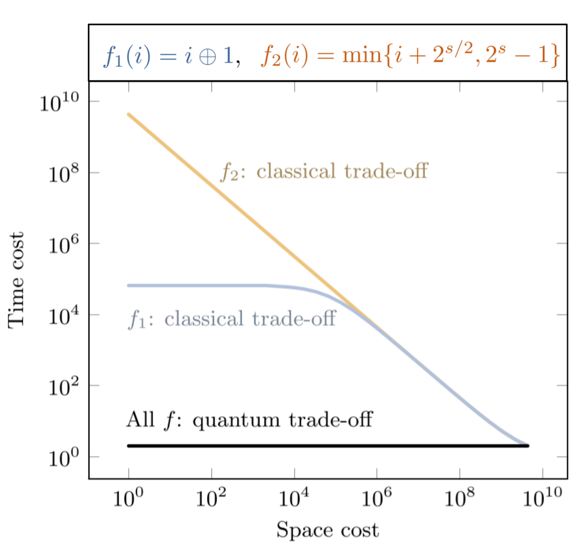


Phys. Rev. X **10**, 041035 (2020)

Project: Quantum advantage in simulating stochastic processes

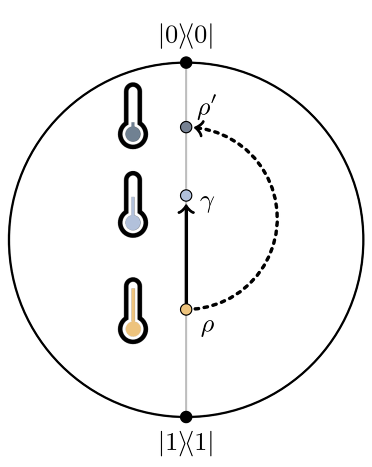
Goal: To understand limits of simulating stochastic processes through quantum dynamics.

Results: Novel quantum advantage phenomenon allowing for the reduction of the amount of memory and time needed to implement certain dynamical processes.

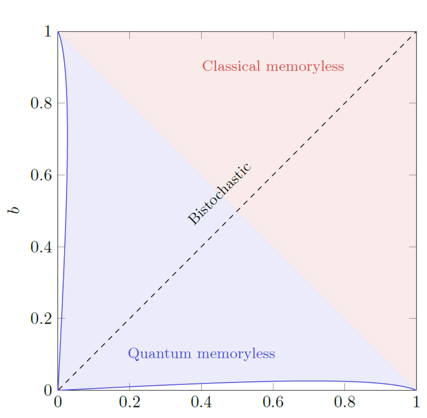


The optimal trade-off between memory cost and time cost of implementing stochastic matrices for a system of s = 32 bits

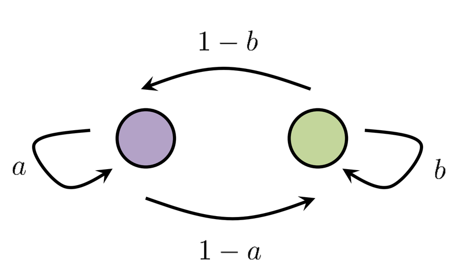
Phys. Rev. X **11**, 021019 (2021)



Classical memoryless thermalizing processes can only cool the initial state of a two-level system to the environmental temperature. Quantum memoryless thermalizing processes allow one to cool the system below that, all the way to the state with the lowest temperature achievable by classical processes with memory.



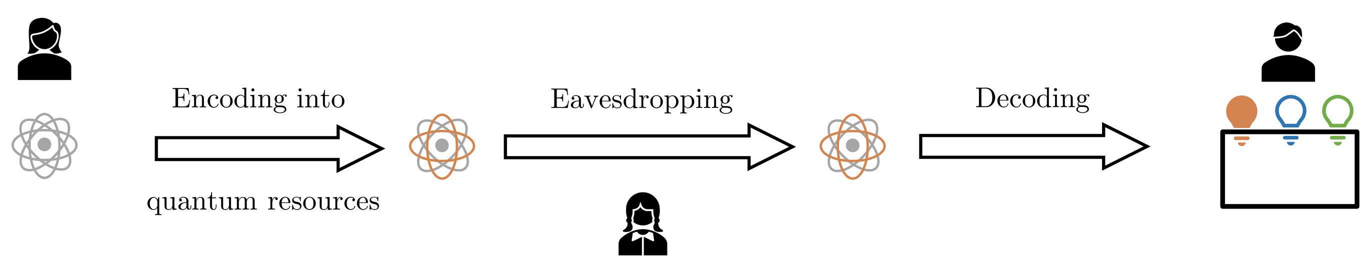
Classical vs quantum memoryless processes for a two-level system.



Quantum Communication

Project: Encoding classical information in quantum resources

Goal: To understand the capacity of quantum resources (like entanglement or coherence) to carry classical information, and how to use them for secure communication.



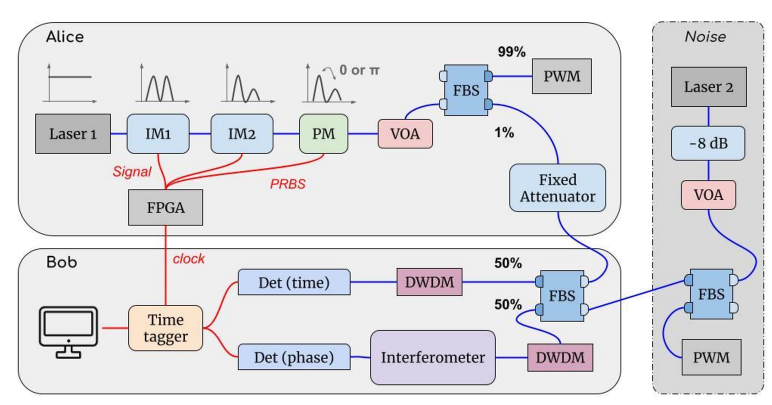
Results: Explicit expressions for optimal communication rates while using encodings into quantum resources (up to second order asymptotic terms) and a proof of security for the communication scheme using a private shared reference frame.

IEEE Trans. Inf. Theory **68**, 4518 (2022)

Project: Allocation of quantum resources

Goal: To formalize the problem of quantum resource allocation in communication networks or multiparty transmission channels according to standard resource allocation criteria.

Results: A theoretical framework that jointly takes advantage of quantum resource theories and the hypergraph language to rigorously formulate the problem of allocating resources in multipartite networks or channels. Also, a communication protocol that takes advantage of the optimal assignment of quantum incompatibility and to study its integration into existing telecommunications infrastructure as well as its resilience to depolarizing noise.



Quantum **5**, 407 (2021)

Project: Dephasing superchannels

Goal: To provide a mathematical model capturing the effects of environmental noise on transmission channels modifying quantum coherence of systems sent between nodes of a network.

Results: Mathematical characterization of every possible environmental effect (superchannel) that preserves a transmission channel's action on incoherent message information, and physical implementations of all such superchannels.

Phys. Rev. A **104**, 052611 (2021)

European Union European Regional Development Fund | Rzeczpospolita Polska | European Funds Smart Growth