Grenoble 6-10 January 2025

ABSTRACT BOOK

All **talk** and **poster** abstracts in alphabetical order of presenter's name

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Correlated quantum machines beyond the standard second law

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The laws of thermodynamics strongly restrict the performance of thermal machines. Standard thermodynamics, initially developed for uncorrelated macroscopic systems, does not hold for microscopic systems correlated with their environments. We here derive exact generalized laws of quantum thermodynamics for arbitrary, time-periodic, open systems that account for all possible correlations between all involved parties. We demonstrate the existence of two basic modes of engine operation: the usual thermal case, where heat is converted into work, and a novel athermal regime, where work is extracted from entropic resources, such as system-bath correlations. In the latter regime, the efficiency of a quantum engine is not bounded by the usual Carnot formula. Our results provide a unified formalism to determine the efficiency of correlated microscopic thermal devices.

Reference paper: https://doi.org/10.48550/arXiv.2409.07899

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Quantum Sensing of Temperature with Interacting Qubit Probes

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Quantum probes, such as single- and two-qubit systems, offer a powerful method for accurately measuring the temperature of a bosonic bath. This work explores how the precision of temperature estimation can be improved through the use of quantum Fisher information and the quantum signal-to-noise ratio. A key result is that introducing an ancilla qubit, which mediates the interaction between the probe and the thermal environment, enhances the thermometric sensitivity by encoding temperature information into the coherence of the probe. We further investigate the use of two interacting qubits, either entangled or separated initially, as quantum probes in various environmental configurations.

Our findings demonstrate that thermometric precision improves as the system approaches a steady state, governed by the interaction between the qubits. This provides a pathway for efficient low-temperature estimation by tuning the qubit-qubit interaction. The study raises important questions about the role of energy dissipation and resource efficiency in quantum thermometry, which is crucial for developing quantum devices that operate near the quantum limit. These results connect to the broader challenge of optimizing energy consumption in quantum technologies, especially in cryogenic environments where precise temperature control is critical for performance.

Experimentally probing Landauer's principle in the quantum many-body regime

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Landauer's principle bridges information theory and thermodynamics by linking the entropy change of a system during a process to the average energy dissipated to its environment. Although typically discussed in the context of erasing a single bit of information, Landauer's principle can be generalised to characterise irreversibility in out-of-equilibrium processes, such as those involving complex quantum many-body systems. Specifically, the relationship between the entropy change of the system and the energy dissipated to its environment can be decomposed into changes in quantum mutual information and a difference in relative entropies of the environment.

In this work, we apply Landauer's principle to experimentally characterise irreversibility in an out-of-equilibrium process in the quantum many-body regime using a quantum field simulator of ultracold Bose gases. Employing a dynamical tomographic reconstruction scheme, we track the temporal evolution of the quantum field following a global mass quench from a Klein-Gordon to a Tomonaga-Luttinger liquid model and analyse the information-theoretic contributions to Landauer's principle for various system-environment partitions of the composite system. Our results agree with theoretical predictions, interpreted using a semi-classical quasiparticle picture.

Our work highlights the capability of ultracold atom-based quantum field simulators to experimentally investigate quantum thermodynamics, providing a powerful platform to explore the interplay of energy, entropy, and information flows in analog quantum simulators.

Light Trajectories and Thermal Shadows casted by Black Holes in a Cavity

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Abstract

We explore the shadows and the photon rings casted by black holes in cavity. Placing the observer inside such an isothermal background, we examine the influence of the cavity temperature T_{cav} and the charge Q on the involved optical aspect. After studying the effect of the horizon radius by varying Q, we investigate the thermal behaviors of the black hole shadows in a cavity. For fixed charge values, we find that the shadow radius r_s increases by decreasing T_{cav}. Varying such a temperture, we discuss the associated energy emission rate. After that, we show that the curves in the $r_s - T_{cav}$ plane share similarities with the $G - T$ curves of the Anti de Sitter (AdS) black holes. Then, we study the trajectory of the light rays casted by black holes in a cavity. We further observe that the light trajectory behaviors are different than the ones of the non-rotating black holes due to the cavity effect. Finally, we provide evidence for the existence of an universal ratio defined in terms of the photon sphere radius and the impact parameter. Concretely, we obtain an optical ratio $\frac{b_{sp}}{r_{sp}} \sim \sqrt{3}$.

Learning efficient erasure protocols for an underdamped memory

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We apply evolutionary reinforcement learning to a simulation model in order to identify efficient time-dependent erasure protocols for a physical realization of a one-bit memory by an underdamped mechanical cantilever.
We show that these protocols, when applied to the cantilever in the laboratory, are considerably more efficient than our best hand-designed protocols. The learned protocols allow reliable high-speed erasure by minimizing the heating of the memory during the operation, and thus reduce the energetic cost of the erasure operation.
More generally, the combination of methods used here opens the door to the rational design of efficient protocols for a variety of physics applications.

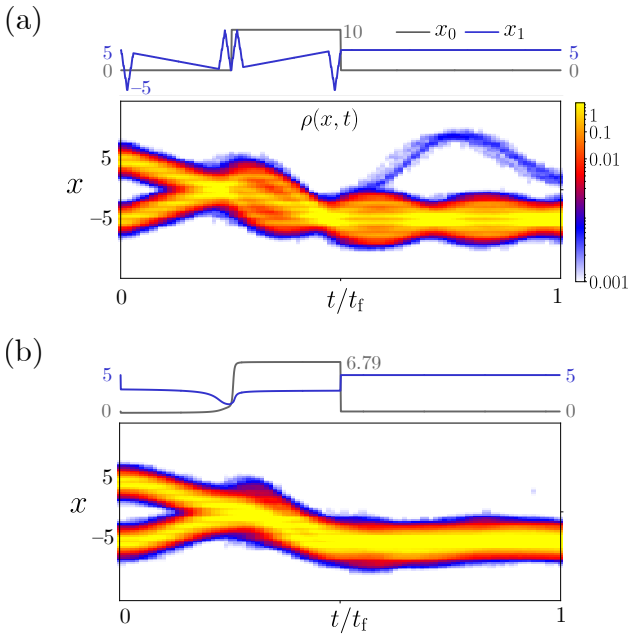

Figure 1: Erasure protocols for a single reset to state 0 (top panels), and the resulting position distributions $\rho(x,t)$ of cantilever positions in experiment. Information is erased as the cantilever begins in either of two states and ends in the lower state. We show (a) our best hand-designed protocol, (b) the protocol trained with machine learning to maximize the success rate and minimize the total energy upon performing a single erasure. The machine-learned protocol is more reliable, and costs less energy to operate.

This work has been supported by project ANR-22-CE42-0022.

[1] N. Barros, S. Whitelam, S. Ciliberto, L. Bellon: arXiv:2409.15050 (2024)

Energetics of classic information erasure: the adiabatic limit

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Information processing in the physical world comes with an energetic cost: Landauer's principle states that erasing a 1-bit memory requires at least kBT0 ln 2 of energy, with kBT0 the thermal energy of the surrounding bath. Practical erasures implementations require an overhead to Landauer's bound, observed to scale as kBT0 B/τ, with τ the protocol duration and B close to the system relaxation time. Most experiments use overdamped systems, for which minimizing the overhead means minimizing the dissipation. Underdamped systems, never harnessed before, thus sounds appealing to reduce this energetic cost.
We use as one-bit memory an underdamped micro-mechanical oscillator confined in a double-well potential created by a feedback loop. The potential barrier is precisely tunable in the few kBT0 range. Within the stochastic thermodynamic framework, we measure both the work and the heat of the erasure protocol. We demonstrate experimentally and theoretically that Landauer's bound can be saturated (within a 1% uncertainty) with quasi-static protocols.
Furthermore, we show that for such underdamped systems, fast erasures induce a heating of the memory: the work influx is not instantaneously compensated by the inefficient heat transfert to the thermostat. This temperature rise results in a kinetic energy cost superseding the viscous dissipation term. Our model covering all damping regimes paves the way to new optimisation strategies in information processing, based on the thorough understanding of the energy exchanges. In this framework, we will in particular consider the adiabatic limit, when both heat fluxes and viscous damping vanish.

This work has been financially supported by the Agence Nationale de la Recherche through grant ANR-18-CE30-0013 and ANR-22-CE42-0022, and by the FQXi Foundation, Grant No. FQXi-IAF19-05.

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Increasing the extracted power in hot-carrier solar cells with energy-filtered contacts

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In conventional solar cells, photogenerated carriers in a semi conductor lose part of their energy before they can be extracted to produce power. This is detrimental to the global power generated by the cell. Hot-carrier solar cells are a broad type of solar cells that try to circumvent this problem by extracting carriers that are still “hot”. The latter can therefore be involved in an electric current flowing against a greater voltage, thus generating more power.
The pratical ways to achieve this can be to focus on improving the material design, for example by reducing the size of the cell so as to make it smaller than the thermal length. Another approach can be to thinking of completely new devices. The work presented in this poster fits in the second category, namely we show, by modelling the device with a Landauer-Buttiker formalism, that the extracted power in a solar cell can theoretically be enhanced by the addition of extra collectors connected to the semi conductor by energy-filtering barriers. For the illustration of the concept, interactions in the semi conductor are neglected, but they can be treated by adding Buttiker probes, see [1].
I will start by discussing the case where a single collector is connected to the semi conductor through a perfect tunnel barrier. By optimizing the height of the barrier and the chemical potential of the collector, the extracted power can be increased by approximately 40% with respect to the unfiltered case. When another collector is contacted to the semi-conductor, through a boxcar-like transmission, the total extracted power can be increased by up to another 40% with respect to the single filter case. This amounts to a doubling of the total extracted power with respect to the unfiltered case. For the sake of theoretical completeness, the case of infinite number of (optimized) boxcars is considered. It is shown that a substantial increase of the total power only occurs for the few first contacts.

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Thermodynamic analysis of a fault-tolerant measurement-free bit-flip quantum memory.

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Quantum computation needs error correction, to get rid of the noise that appears in the qubits. This process produces entropy, and therefore induces a dissipation of energy. To better understand what would be the energy consumption of a quantum computer, one needs to perform a thermodynamic analysis of the error correction process. To do so, it is interesting to study the entropy flow in an error correction code, and look for additional behaviors and limits to the entropy production, than the Landauer limit. We are studying this in the simplest fault-tolerant error correction code, that only corrects bit-flip errors.

For that, we designed a measurement-free fault-tolerant version of the bit-flip quantum memory, and we have started to analyse entropy flows within it.

Stochastic information processing in a lazy quantum measurement engine

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Quantum measurements allow for information extraction and can affect the average energy of the measured quantum system via their backaction [1]. These possibilities are at the heart of many promising quantum technologies and computing methods [2] and we study their energetic consequences and effects on the evolution of a single-qubit engine.

On the one hand, information processing allows for efficiency feedback protocols by which a working substance's entropy can be reduced. Maxwell-demon type engines operate along these lines. However, information processing is also known to have an energetic cost when an irreversible memory reset is implemented, this is the famous Landauer erasure cost.

On the other hand, measurement backaction also can have energetic consequences, since measurement can affect the average energy of quantum systems. This purely quantum phenomenon has interesting consequences. Especially, when the working substance can interact with a bath, measurement backaction can fuel a quantum engine without requiring any information processing [3].

Quantum engine can also run without connecting the working substance to a thermal bath, moving one step farther from classical thermodynamics [4]. To witness the interplay between the backaction and the information extraction facets of quantum measurement, such a quantum measurement engine with a simple working substance is ideal. We allow for laziness in information processing, i.e., the engine stochastically runs blindly, only using measurement for its backaction, without using the outcome information in a feedback step. This reveals a quantum to classical tug-of-war where laziness disturbs work extraction while it reduces information processing cost.

We show that the work extracted over consecutive cycles is a second-order Markov process, analogous to a run-and-tumble process with transient anomalous diffusion. We derive exact analytical expressions for the work finite-time moments and first-passage-time statistics. Furthermore, we find the optimal laziness probability maximizing the mean power extracted per cycle.

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Energy additivity as a requirement for universal quantum thermodynamical frameworks

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The quest to develop a general framework for thermodynamics in the regime of strong coupling and correlations between subsystems of an autonomous quantum “universe” has entailed diverging definitions for basic quantities, including internal energy. While most approaches focus solely on the system of interest, we propose that a universal notion of internal energy should also account for the environment to keep consistency with the closed-system energy of the universe. As an illustration, we present a particular two-qubit universe model, obtaining the exact master equations for both parties and calculating their effective Hamiltonians and internal energies as given by the recently devised minimal dissipation approach. In this case, we show that internal energies are not additive, which leads to unphysical features. Finally, we introduce an abstract framework to describe all effective Hamiltonian-based approaches and address a rigorous definition of energy additivity in this context, in both a weak and a strong forms, discussing the underlying subtleties [1].

[1] arXiv:2408.04111

Green is the new black

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That software moves the world is a clear fact. And that it is becoming more and more important, too. There are three aspects that have led to an increase in the intensity with which software is used: the Internet and social networks, data and artificial intelligence.

However, not everything is positive in the support that software provides to our daily lives. There are estimates that ICT will be responsible for 20% of global energy consumption by 2030, part of which will be due to software. And precisely the three mentioned aspects require large amounts of energy.

In this keynote we will review different concepts related to software sustainability, and we will show some results of software consumption measurements that we have carried out on the one hand, cases carried out to raise awareness in society in general about the impact that software has on the environment. On the other hand, examples related to the consumption of software carried out with the aim of creating a set of best practices for the software professionals. Among them, some examples of comparison on the energy consumption of classical vs. quantum algorithms will be also shown.

Our ultimate goal is to make you aware of the consumption problem associated with software and to ensure that, if at first, we were concerned with the *"what"* and later with the *"how"*, now it is time to focus on the *"with what"*.

Biography

Coral Calero is a Professor at the University of Castilla-La Mancha in Spain and has a PhD in Computer Science. She is a member of the Alarcos Research Group, being responsible of the "Green and Sustainable software" line research, where two main lines of work are developed. The first addresses issues such as measuring the environmental impact of the software and how to improve its energy efficiency, as well as human and economic aspects related to software sustainability. The second major line of work supports the dissemination activities to raise awareness of the impact that software has on the environment. Since its creation in 2023, she has been one of the 12 members of the Spanish Research Ethics Committee.

Extending the self-discharge time of Dicke quantum batteries using molecular triplets

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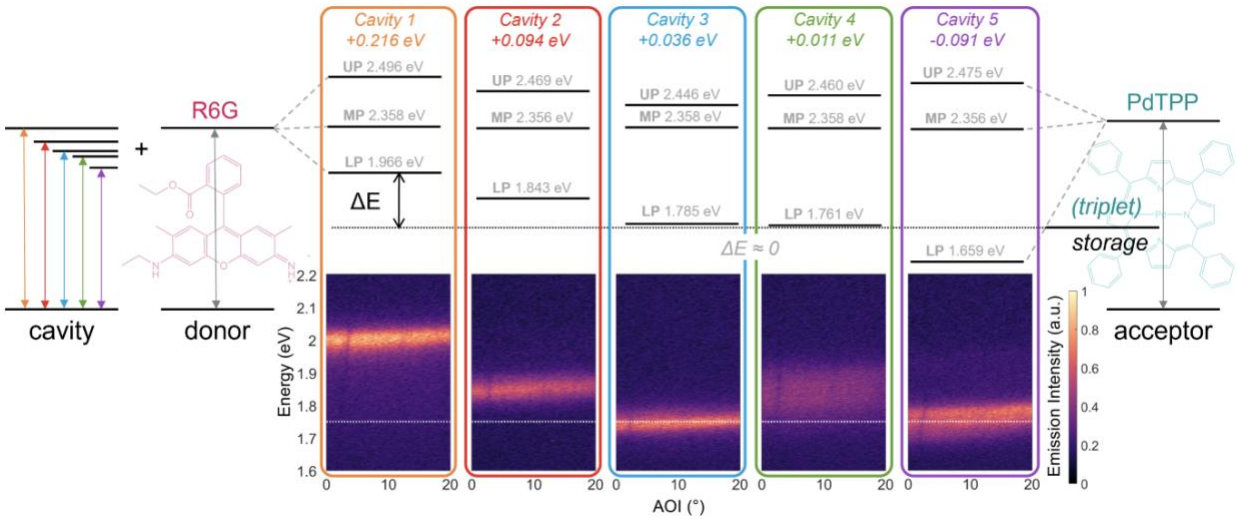

Recent years have witnessed an explosion of interest in quantum devices for the production, storage, and transfer of energy. Quantum batteries are one of such devices that have emerged from fundamental research in quantum thermodynamics. In the last five years they have gained interest due to the potential of achieving charging power that scales super-extensively with the number of components [1], which is linked to entanglement growth in closed many-body quantum systems. This has led to an interdisciplinary effort aimed at finding quantum battery architectures that would display such power scaling. A particularly successful quantum battery proposal, based on the Dicke model, has been explored experimentally using organic microcavities, which enable a cavity-enhanced energy transfer process called superabsorption. However, energy storage lifetime in these devices is limited by fast radiative emission losses, worsened by superradiance.

In this work, we demonstrate a promising approach to extend the energy storage lifetime of Dicke quantum batteries using molecular triplet states. We examine a type of multi-layer microcavities where an active absorption layer transfers energy to the molecular triplets of a storage layer, identifying two regimes based on exciton-polariton resonances. We tested one of these mechanisms by fabricating and characterising five devices across a triplet-polariton resonance. In this talk, we will also discuss how this approach can also be translated to quantum battery architectures based on "ultra-cold" quantum technologies, such as Rydberg atoms, trapped ions, and superconducting qubits, which might find application as an enabling technology for quantum computing and simulation [2].

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Potential Barriers Make Quantum Thermoelectrics with Nearly Ideal Efficiency at Finite Power Output

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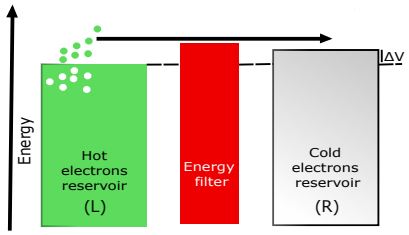
Abstract

Quantum thermodynamics defines the ideal quantum thermoelectric, with maximum possible efficiency at finite power output. However, such an ideal thermoelectric has not yet been implemented experimentally. Thus, instead, we consider two thermoelectrics regularly implemented in experiments: (i) a single-level quantum dot and (ii) a potential barrier or quantum point-contact. We model them with Landauer scattering theory as, respectively, (i) Lorentzian transmission or (ii) step transmission. We optimize their efficiencies as heat-engines and refrigerators at given power output. The Lorentzian's efficiency is excellent at vanishing power, but it is found to be poor at the finite powers of practical interest. In contrast, the step transmission is remarkably close to ideal efficiency (typically within 15%) at all power outputs. The step transmission is also close to ideal in the presence of phonons and other heat-leaks, for which the Lorentzian performs very poorly. Thus, the simplest nanoscale thermoelectrics (potential barriers and point contacts) are also about the best.

Landauer-Büttiker Scattering Theory

Quantum thermoelectrics are nanostructures that can act as energy filters, and their behavior can be explained using the Landauer-Büttiker scattering theory.



- Heat current:

$$J_L = \frac{1}{h}\sum_{\mu}\int_0^{\infty} \mathrm{d}\varepsilon\varepsilon \mathcal{T}^{\mu\mu}_{RL}(\varepsilon)\left[f^{\mu}_{L}(\varepsilon) - f^{\mu}_{R}(\varepsilon)\right]$$

- Power generated:

$$P_{\text{gen}} = \frac{1}{h}\sum_{\mu}\int_0^{\infty} \mathrm{d}\varepsilon\mu eV \mathcal{T}^{\mu\mu}_{RL}(\varepsilon)\left[f^{\mu}_{L}(\varepsilon) - f^{\mu}_{R}(\varepsilon)\right]$$

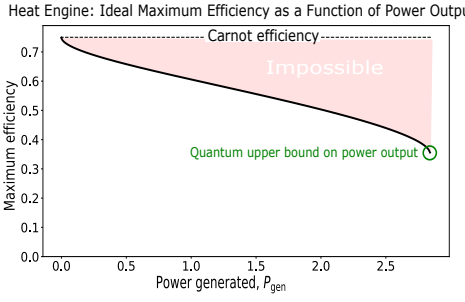
- Heat engine efficiency:

$$\eta_{\text{eng}} = \frac{P_{\text{gen}}}{J_L} \leq \eta^{\text{Carnot}}_{\text{eng}}$$

The Ideal Quantum Thermoelectric

In 2014, Whitney found that the boxcar transmission function is optimal [1], making the ideal quantum thermoelectric, **but it's not achieved in experiments**.

Heat Engine: Ideal Maximum Efficiency as a Function of Power Output

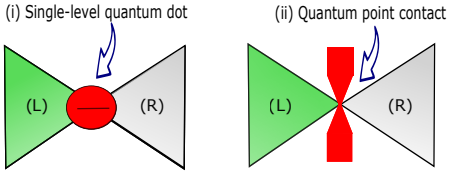


Experimentally Accessible Quantum Thermoelectrics

Two quantum thermoelectric systems commonly used in experiments are:

(i) Single-level quantum dots [2].

(ii) Potential barriers and quantum point contacts [3].



(i) **Lorentzian transmission** $\longrightarrow \mathrm{T}(\varepsilon) = \frac{\Gamma^2}{(\varepsilon-\varepsilon_0)^2+\Gamma^2}$

(ii) **Step transmission** $\longrightarrow \mathrm{T}(\varepsilon) = \frac{1}{1+e^{-\frac{(\varepsilon-\varepsilon_0)}{T}}} \overset{\Gamma \ll k_B T}{\longrightarrow} \theta(\varepsilon-\varepsilon_0)$

Method

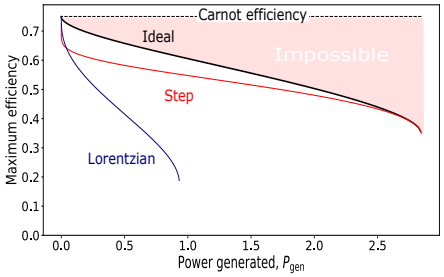
To optimize the two experimentally accessible systems and determine which one is the best, we used the Lagrange multiplier method, which includes:

1) $\mathcal{L}_{\text{eng}}(x_1,\cdots,x_n,\lambda) = \eta_{\text{eng}}(x_1,\cdots,x_n) - \lambda\left[P - P_{\text{gen}}(x_1,\cdots,x_n)\right]$

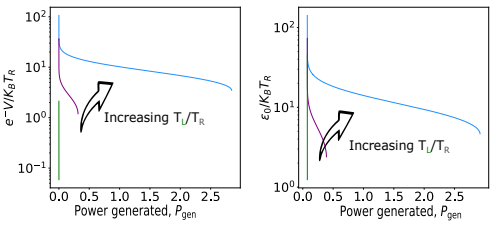
2) $\nabla_{x_1,\cdots,x_n,\lambda}\mathcal{L}_{\text{eng}}(x_1,\cdots,x_n,\lambda) = (0,\cdots,0)$

Results and Discussion

Heat Engine: Maximum Efficiency for Ideal, Step, and Lorentzian Transmission

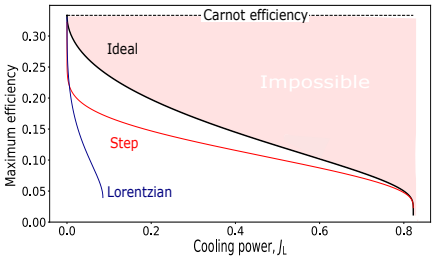


Heat Engine: Optimal Parameters for the Step Function



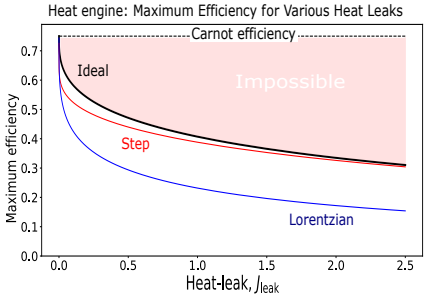
- The step transmission function achieves nearly 15% of the ideal efficiency across all power outputs.
- The Lorentzian transmission only approaches optimal efficiency at very low power outputs.

Refrigerator: Maximum Efficiency for Ideal, Step, and Lorentzian Transmission

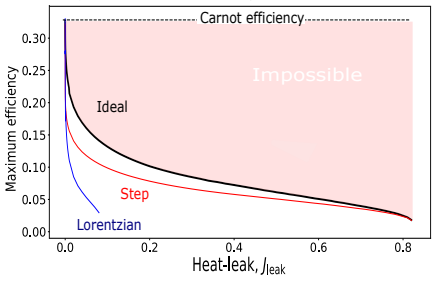


- For refrigerators, the step is mostly also within 15% of the optimal.

Heat engine: Maximum Efficiency for Various Heat Leaks



Refrigerator: Maximum Efficiency For Various Heat Leaks



- When considering heat leaks, the step transmission function remains the best.

Conclusion

The maximum efficiency for the step transmission is close to ideal in both heat engines and refrigerators. It is also near ideal in the presence of heat leaks, making potential barriers and point contacts the best experimentally implemented thermoelectrics.

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EXTRA COST OF ERASURE DUE TO QUANTUM LIFETIME BROADENING (QEI2025)

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The energy cost of erasing a bit of information was fundamentally lower bounded by Landauer, in terms of the temperature of its environment: $W \geq k_{\mathrm{B}}T \ln 2$. However, in real electronic devices, the information-bearing system is usually in contact with two or more electrodes, with different temperatures and chemical potentials. It is not clear what sets the cost of erasure in such nonequilibrium situations. One promising technology for testing the thermodynamic limits of information processing is quantum dots, in which a bit is encoded in the presence or absence of a single electron. We here develop a thermodynamic description of devices of this type and find that, in addition to the electrode temperatures, the potential difference across the quantum dot and lifetime broadening of its energy level contribute to the minimum work cost of erasure. In practical contexts, these contributions may significantly outweigh the cost due to temperature alone.

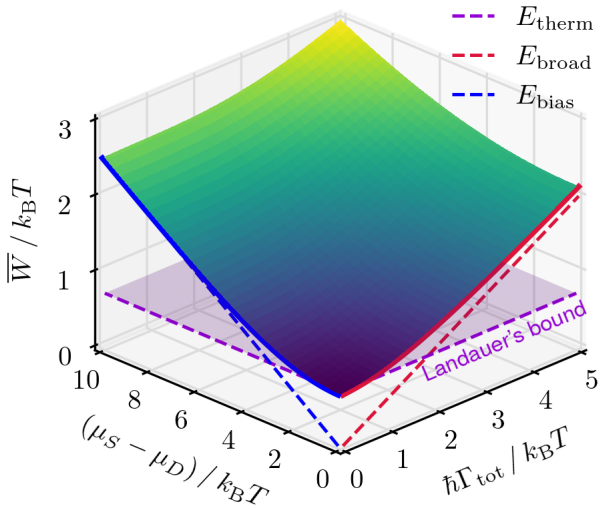

Figure 1. The optimal average work cost of erasure W for a quantum dot in contact with two electrodes, plotted against source-drain bias ($\mu_S - \mu_D$) and lifetime broadening ($\hbar\Gamma_{tot}$), at temperature T. At zero bias and zero broadening, an ideal erasure process can saturate the Landauer bound, $W \geq k_{\mathrm{B}}T \ln 2$. However, if either $\mu_S - \mu_D$ or $\hbar\Gamma_{tot}$ exceeds a few times k_BT, then the work cost is significantly larger.

Information Structure in Multi-time Quantum Processes

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Information processing and control of quantum systems with non-classical correlations over multiple time steps are the subjects of intense focus in recent years. Such tasks can greatly benefit from accounting for the intrinsic informational structures in the quantum process involved. For example, an observer whose goal is to predict a quantum process's future outputs seeks to minimize the uncertainty of their predictions while using the least resources possible. This begs the following question: What are the fundamental limits of predictability of a quantum process? By imposing the lens of input-output processes [1] from computational mechanics onto the framework of process tensors [2] which is an operationally consistent multi-time characterization of non-Markovian quantum processes, we define and quantify structural features along the lines of randomness and complexity [3] in stationary quantum processes. The central object quantifying the intrinsic randomness is the process Choi state entropy rate which is shown to have a conditional form for stationary processes and further leads to the formalization of a notion of process memory as the quantum excess entropy. Our results provide foundational tools to examine and compare quantum processes, and opens up possibilities in obtaining fundamental limits in operational contexts such as quantum predictive modelling, quantum communication and cryptography, and quantum thermodynamic work extraction.

Having a quantum entropy rate can allow us to quantify the degree of irreversibility and energy dissipation rate in a quantum process. There is also a possibility in applying our results to provide an upper bound of an asymptotic work extraction rate by a quantum information engine which extracts useful work from patterns in a multi-time quantum process. Such protocols have been proposed for classical stochastic processes [4] and those with classically correlated quantum outputs [5]. Our work introduces new tools which may enable the analysis of generalized quantum information engines extracting work from fully quantum processes with spatiotemporal quantum correlations.

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Challenges in realizing Quantum Simulation of Dissipative Spin Dynamics (QEI2025)

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Computational bottlenecks in simulating open quantum systems for large system sizes restricts our capacity to theoretically probe interesting quantum phenomenon[a,b]. In the context of optimal quantum control protocols for example, sub-routines involving propagator calculations for Hamiltonians describing dissipative spin systems of realistic complexity, often requiring the need to simulate the full Liouville space description, are well known to be prohibitively costly. This adds to the myriads of other arguments for why efficiently emulating the evolution of quantum systems on quantum hardware is the most pressing near-term goal for quantum computers[c,d], both digital and analogue. We consider the problem of efficiently simulating the full open quantum systems description of the complex quantum spin dynamics of radical pairs for system sizes beyond the reach of state-of-the-art methods for classical simulation of quantum systems. This allows us to bring to light challenges in scaling up digital quantum simulations of utilitarian value on near term quantum hardware and suggest specific improvements to bring them within reach.

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Energy consumption of a neutral atom QPU for two use-cases (QEI2025)

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We aim to estimate the computational cost and energy consumption, and the effects on the environment, of running state-of-the-art classical numerical techniques associated with solving two use cases. First we consider an experiment for a Transverse Field Ising Model (TFIM) and then the instances of a Maximum Independent Set (MIS) problem. We benchmark against emulations of the QPU and the total energy consumed by the a quantum device while tackling these use cases. To solve the Ising model, our methods include Exact Diagonalization, Tensor networks (MPS and PEPS), and Monte Carlo. When addressing the Maximum Independent Set (MIS) problem, we employ a quantum approach provided by Pasqal and benchmark its performance against state-of-the-art optimization techniques.s

Quantum thermodynamics under the lens of density functional theory

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Accurate calculations of properties such as the energy of many-body quantum systems can be done using density functional theory (DFT). This has provided over the years various predictions of material properties as well as multiple aids to the interpretation of experiments [1]. However, while ground state DFT is very well developed, DFT for strongly out-of-equilibrium dynamical systems and thermal DFT and is much less so [2]. Interest in this direction has been renewed by the development of more complex quantum technology devices and by the advent of quantum thermodynamics. The effects of many-body interactions on thermal machines have started to be considered only recently[3]; however, from a theoretical point of view, addressing the study of interacting many-body quantum systems at finite temperature and out-of-equilibrium demands significant effort, usually requiring the use of approximations to tackle the complexity of problems beyond a handful of particles.
In this context, we discuss the possibility of using DFT as a way to study the out-of-equilibrium thermodynamics of interacting many-body systems. We first apply this approach to the calculation of the work from out-of-equilibrium finite-time finite-temperature dynamics using concepts and tools from zero-temperature DFT [4]. We then propose an approach based on finite-temperature (thermal) DFT to extrapolate information about the statistics of work and the irreversibility of sudden quenches [5]. In particular, we demonstrate that, in this case, both the characteristic function of work and that of irreversible entropy production can be expressed as functionals of the local finite-temperature equilibrium densities of the pre- and post-quench Hamiltonians. This positions these densities as fundamental variables to derive information on the thermodynamic processes.

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Electrical energy cost of arbitrary state preparation with programmable integrated photonic circuits

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Over the past decade, significant progress has been made in both gate-based and measurement-based quantum devices photonic integrated circuits (PICs) for tasks such as quantum information processing (QIP), quantum state preparation (QSP), and quantum simulation (QS) (*1*, *2*). However, the scalability of these tasks using photonics remains limited. In order to begin approaching relevant quantum tasks, circuits must implement states with $\mathcal{O}(10^2)$ to $\mathcal{O}(10^3)$ qubits (*3*) which brings energy consumption into focus (*4–6*).

To perform a quantitative evaluation of the energy consumption of quantum PICs, we constrain our analysis to arbitrary QSP (aQSP). We have chosen aQSP for two reasons: it allows for a more general treatment, as opposed to QIP, which would require selecting one or more algorithms for comparison, and encoding information on a quantum state is a preliminary task to QIP and is a core task of algorithms such as variational quantum eigensolvers (VQE) (*7*).

Central to integrated quantum photonic devices are programmable Mach-Zehnder Interferometers (MZIs), which, with their tunability via phase modulators, serve as tunable beam splitters. This tunability is crucial for reconfigurable circuits and correcting fabrication imperfections. The main question which we address in this work is the power consumption to implement aQSP, in the context of the energy spent to program PICs consisting of arrays of MZIs using electro-optical modulators (EOMs), which are already more energy efficient than the more commonly used thermal-optical modulators.

We compare the energetic cost for aQSP using qubits and qudits. Decomposition algorithms exist for square meshes of MZIs to implement any arbitrary unitary with a dimension defined by the number of ports of the array (*8*), so aQSP of a qudit state can be performed deterministically. Although qudits require 2^n waveguides to implement a state equivalent to n qubits, we see that a fully programmable qudit processor can be more energy efficient. This is due to the fact that qubit aQSP requires a number of CNOT gates exponential in n, and implementing a CNOT on a programmable interferometer requires setting several phases to their most energy expensive values.

We show that a fully programmable interferometer array that implements gate-based protocols optimized in the number of CNOTs reaches a power consumption in the 10 MW to 100 MW range for 30 qubits and programming times in the order of seconds to minutes (*9*). Scaling up to just 100 qubits already makes either the power consumption or the programming time become prohibitive. This can be circumvented for qubits, using fixed CNOT modules that keep a minimal degree of tunability to compensate for fabrication errors, but not for qudits. This solution is not available for measurement-based strategies, as an exponential number of measurements must be programmed to fulfill the QSP task.

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Towards Quantum Energetic Advantage in Boson Sampling (QEI2025)

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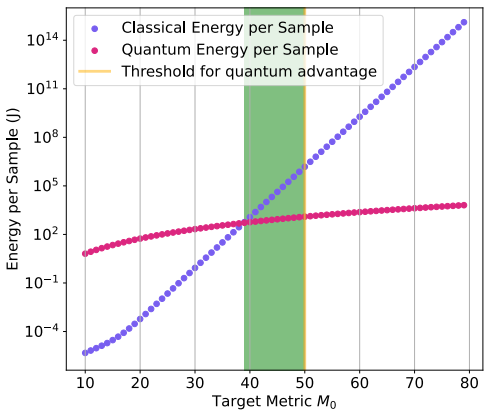
Quantum computation is rapidly advancing, leveraging the principles of quantum mechanics to solve problems that are computationally intractable for classical systems. As quantum devices scale up, optimizing their energy consumption becomes increasingly critical. Energy efficiency not only reduces operational costs but also minimizes the environmental impact of emerging quantum technologies [1,2]. Moreover, exploring the concept of a **quantum energetic advantage**—where a quantum computer completes tasks using less energy than the best classical counterparts—adds a new layer of motivation for advancing quantum technologies.

While the computational speed-up of quantum devices has been widely studied, their energetic aspects have gained attention only recently. The **Metric-Noise-Resource (MNR) framework** provides a systematic approach to quantify and optimize resource consumption in quantum systems [3]. By linking a performance metric to underlying noise processes and resource requirements, the MNR framework enables a detailed analysis of the trade-offs between computational performance and energy use.

In this work, we apply the MNR framework, for the first time, to **Boson Sampling**, a computation problem that is considered a strong candidate for demonstrating quantum advantage [4]. Boson Sampling involves generating samples from the output distribution of indistinguishable photons passing through a linear optical network—a problem that quickly becomes intractable for classical computers as the system size increases.

By defining the control parameters, performance metric, noise processes, and resource consumption specific to Boson Sampling, we highlight the trade-offs between key factors such as system size, operational temperature, photon indistinguishability, and the energy required for computation [5,6]. In particular, we pinpoint a trade-off between quantity and quality of single photon: an increase of the number of input photons lead to a decrease of the indistinguishability of single photons at fix cryogenic power.

By comparing the energetic cost per sample for quantum and classical implementations, we explore the conditions under which a **quantum energetic advantage** can be realized. State-of-the-art classical algorithms and supercomputers provide the baseline for classical energy consumption [7,8]. Our results show that quantum implementations can achieve lower energy per sample compared to classical methods, even when factoring in realistic noise and system losses. We obtain an energetic advantage without a computation advantage in the green region (see figure right) for the task of Boson Sampling.



This study underscores the importance of integrating energy efficiency into the design of quantum technologies. Demonstrating the potential for a quantum energetic advantage in Boson Sampling extends the value of quantum computation beyond mere speed-up, emphasizing energy efficiency as a critical factor in the future of scalable quantum systems. As quantum devices evolve toward practical applications, energy considerations should play a pivotal role in their development and optimization.

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Quantum computing roadmaps and their energetics aspects

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The Quantum Energy Initiative was initiated over three years ago now and has taken shape with the creation of an academic community. Now is the time to look at the challenges ahead of us. Indeed, meanwhile, many scientific and technological advances have been realized by both academic teams and industry vendors, including the creation of larger quantum computers with better qubit fidelities and the first logical qubits operating above breakeven. These advances provide a better understanding of the scalability challenges and their impact on the energy consumption of these solutions.

The presentation shows in a full-stack holistic view how recent scientific progress in scaling quantum computing is bringing new solutions and new questions on the energetics of these systems, particularly when considering FTQC roadmaps.

It starts with refining the definition of a quantum energy advantage, both in the NISQ and the FTQC regimes, and lays out the interconnection between the economics of quantum computing and its viable applications, which impacts their potential resource estimates and energy consumption. It shows how utility-grade algorithms resource and time estimates bring new questions on the power cost of quantum computing, showing the contrast between theoretical and practical quantum advantages.

It then covers the interdependencies between quantum computing viable applications requirements and the related classical computing costs, qubit designs, qubit gate and readout times, manufacturing constraints, quantum error correction techniques, the new critical role of quantum processor interconnect and how enabling technologies are scaling. It shows how systems architecture design strongly influences the energetic footprint of FTQC quantum computers. The overarching role of the presentation is to propose new research avenues that connect quantum science and engineering with the Quantum Energy Initiative goals.

RISE OF QUANTUM COHERENCES

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The first part of the talk will contribute to this understanding by widely demonstrating the counter-intuitive emergence of single-qubit coherence in different regimes at a low temperature. A typical setup to generate coherence in a qubit, a two-level system, or their ensembles requires a solid and coherent external input to drive the system, often leading to a linearisation of the dynamics. Here, we use merely a low-temperature limit of an oscillator coupled to the qubit to generate qubit coherences with any external drive. Diverse models can be implemented in various experimental platforms, such as trapped ions, superconducting circuits, or solid-state qubits, for their qubit transients and steady states. We demonstrate how engineered nonlinear dynamics can produce significant coherence in the qubit from small incoherent thermal energy across a wide range of parameter values [1-8].

In the second part, we address the rise of quantum non-Gaussian coherences in atoms and similar systems crucial for advancing quantum technology. Despite their significance, there are still open challenges in comprehending them deeply, generating and controlling them autonomously, detecting them reliably, and providing conclusive certification. New theories on quantum non-Gaussian coherence of atomic motion represented by off-diagonal elements on a Fock state basis will be briefly overviewed and summarized. The talk will highlight the emergence of autonomous quantum non-Gaussian coherence by cooling and decaying interacting systems to the ground state and its structure [9]. Additionally, it will illustrate that nonlinear motional couplings of atoms can give rise to quantum non-Gaussian coherences stimulated by small energy of a few thermal quanta [10].

Lastly, the talk will introduce a new, experimentally tested and unpublished rise and classification of quantum non-Gaussian coherence in the continuous variable picture, essential in understanding the abovementioned phenomena.

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Low-Distance Surface Code Emulation for Silicon-based Spin Qubits

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The last few years have seen significant progress in the field of silicon-based quantum technology, consolidating the development of single-qubit and two-qubit gates with increasing controllability and fidelity [1–3]. A key component for the realization of a large-scale fault-tolerant quantum computer is quantum error correction (QEC), which shields quantum information from decoherence effects, providing exponentially scalable resilience to noise. In this work, we report the logical qubit performance of the 17-qubit rotated surface code, based on the emulation of a realistic noise model on the Qaptiva quantum computing emulator, developed by Eviden. We rely on physical level simulations to derive noise models for one and two-qubit gates, considering two sources of noise acting on the Larmor frequency and the exchange energy. Strategies have been initiated on improving their fidelity, leading to the introduction of gates more resilient to noise. We then perform an optimization of the syndrome extraction circuit using Si-qubit technology native gates, yielding a circuit of 68 gates and depth 10. Further, we introduce a new performance metric of the logical qubit, referred to as logical qubit coherence time ($T^*_{2,L}$), obtained by performing a Ramsey-like experiment on the logical qubit, and providing a performance metric directly comparable against the coherent time of the physical qubit (T^*_2). In the absence of exchange energy noise, our numerical results reveal a significant enhancement in the logical qubit coherence time compared to the physical one (Fig. 1). However, upon introduction of noise in the exchange energy, the error contribution from two-qubit gates becomes predominant, resulting in a saturation of logical qubit performance for increasing T^*_2. Additional simulations have also been conducted, providing a fine characterization of the error correction performance for different regions of the (T^*_2, T^*_J) parameter space.

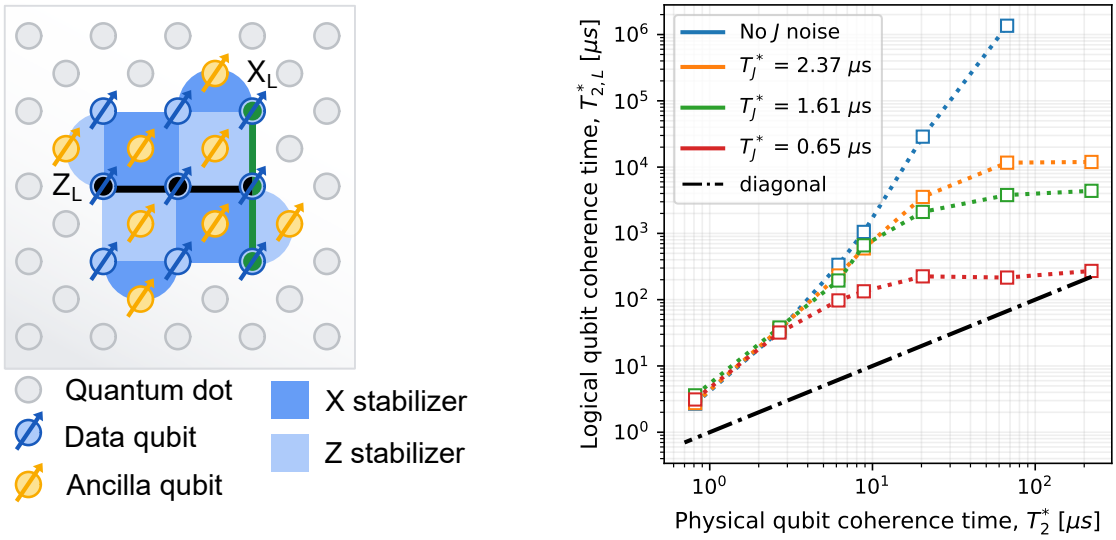

Fig. 1: (Left) Distance-3 rotated surface-17 code on a 2D layer of spin qubits. Data qubits are represented in blue and ancilla qubits in yellow. Dark and light blue patches represent X and Z stabilizers, respectively. (Right) logical qubit coherence time $T^*_{2,L}$ as a function of T^*_2, for different two-qubit coherence time values, T^*_J, induced by exchange energy noise. In the absence of exchange energy (J) noise, the logical qubit coherence time scales as $T^*_{2,L} \propto (T^*_2)^4$, for $T^*_2 \geq 10\,\mu$s. We observe that low T^*_J saturates the logical qubit coherence time, rendering improvements on T^*_2 ineffective.

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Transport-based quantum tomography in open quantum systems

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In this talk, I will present a novel scheme for achieving quantum tomography in open quantum systems, based solely on transport quantities, currents and their fluctuations. I will show that the density matrix's elements of a two-qubit system in an open system configuration can be entirely reconstructed without performing additional Pauli measurements. These results pave the way to another demonstration that uncontrolled dissipation does constitute a resource for quantum information processing. As a direct application, we provide an exact expression of an entanglement witness in terms of non-equilibrium steady-state transport quantities only.

Reference: J. Bourgeois, G. Blasi, G. Haack, *manuscript in preparation (2025)*.

Quantification of energy consumption of quantum resource generation QEI2025

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One of the main tasks of quantum information processing is generating, manipulating, and using quantum resources. Prominent examples of such resources are quantum entanglement and quantum secret key, which are planned to be used in future quantum networks, e.g., for distributed quantum computing and secret communication, respectively. In these networks, quantum resources will be distributed via quantum channels. Due to channels imperfections, this process is expected to involve energy consumption. The consumption takes place during both passing input to the channel and the distillation of imperfect resources taken from the channel's output to its almost perfect form. For this reason, we propose estimating and minimizing this consumption as one of the important tasks on the way to economical quantum information processing.

We then establish a quantitative study of energy expenditure in producing quantum resources via quantum channels. We distinguish technological and fundamental energy costs. Technological cost depends on hardware; hence, it is not a fixed quantity. We then focus mostly on the fundamental one. We provide a general definition for the minimal, i.e., unavoidable fundamental energy consumption in creating a maximally resourceful state expressed with the units of Jule per rbit (energy invested while generating a unit of resource). We then provide an upper bound on this quantity in case of generated quantum entanglement encoded as polarization of photons, based on the original BBPSSW quantum entanglement distillation protocol.

We further derive a lower bound on the fundamental energy cost of the standards procedure of entanglement generation (taking maximally entangled states as input to the channels). Hence, under the current design, we provide a quantitative estimate (a lower bound) of the inevitable energy consumption in future quantum networks.

Calorimetric detection of single electron tunneling events

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Among the many ways of implementing quantum bits, single spins stand out due to their long coherence times and prospect for large-scale integration. Readout of the spin state generally requires tunneling of an electron into a reservoir, dissipating an energy in the order of ~meV at each repetition. [1,2]
At a rate of 1 MHz, this already amounts to ca. 100 aW of heating, which, given the ultra-small size and low operating temperatures, increases significantly the temperature of the reservoirs and therefore reduces the readout fidelity. [3]
In order to quantitatively study this heating effect, we here seek to construct a detector capable of measuring the heat produced by an electron tunneling from a quantum dot into a nearby reservoir; in other words, we want to achieve calorimetric detection of single tunneling events.
To this end, a micron-sized thermal absorber constitutes the drain reservoir of an epitaxially defined quantum dot in an InAs nanowire. A proximitized tunnel junction across the absorber serves as a sensitive thermometer and radio-frequency measurements will be employed for readout on the µs-timescale. [4]

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Conception of cryo-attenuators for dilution fridges

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While commercial dilution refrigerators offer a base plate at less than 10 mK, thermalizing the microwave modes themselves turns out to be more challenging than just anchoring the superconducting circuit to the plate. Effectively, superconducting qubits are coupled to a heat bath that is often in the 50-100 mK range, which drastically downgrades their coherence time. A key element to getting lower effective temperatures is the microwave attenuator that is the closest to the quantum circuit. Recent progress has been made by a couple of companies using conductive casing (gold coated copper) instead of stainless steel. However, the dissipative elements are thin films that are not able to evacuate Joule power (up to about 100 nW) well enough into the dilution refrigerator. This is particularly detrimental for quantum error correction or amplification, which both require strong microwave drives.

At low temperature (i.e below 1K), the conduction of heat is done by the electrons whereas it is done by the phonons at room temperature, this phenomena together with the Wiedemann-Franz law which links the electrical conductivity and the thermal conductivity of electrons in a normal metal explain the unperfect thermalization of the attenuators at 10 mK.

The idea proposed in the Quantum Circuits groups to better thermalize attenuator at low temperature is based on a coplanar waveguide (CPW) geometry together with a choice of materials enabling good thermalization of the modes. This solution has the advantage to go over the Wiedemann-Franz law and decouple the thermal and electric currents.

In the poster, the fabrication process of the attenuator, simulations and measurements of the attenuation will be presented

Clean baths, clean qubits: thermodynamics of solid-state purification (QEI2025)

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Stable quantum coherence is essential for processing quantum information. Solid-state qubits decohere due to interactions with a complex environment. However, recent experimental advances have demonstrated that decoherence can be suppressed by repeatedly measuring and controlling these qubits, thereby modifying their surrounding bath. In this way the bath is engineered to shield the qubit from decoherence. These so-called purification protocols function as Szilard engines, regulating the flow of energy and entropy between the qubit and its environment. A microscopic treatment of the thermodynamics of these purification protocols is challenging, as it must account for finite-size effects of the bath, system-bath correlations, and often assumes a complex bath spectrum. In this work, we focus on two realistic solid-state Szilard engines: a superconducting qubit and a spin-qubit in a semiconducting quantum dot. We perform microscopic derivations that provide access to joint system-bath quantities. Our results reveal the limitations imposed by interactions and the laws of thermodynamics across all relevant time scales of the purification processes.

Cyclic Solid-State Quantum Battery: Thermodynamic Characterization and Quantum Hardware Simulation

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Quantum batteries have become a promising candidate for studying energy management in nanodevices. In this regard, we propose a cyclic quantum battery model, based on an interacting bipartite system, weakly coupled to a thermal bath. The introduced cycle of the battery consists of four strokes: system thermalization, disconnection of subsystems, ergotropy extraction, and reconnection. In the thermalization stroke, the thermal bath acts as a charger, and ergotropy extraction is possible because the thermal state is not passive after the disconnection. Exploitation of interaction between a battery and a charger composed of the whole model allows us to demonstrate the high performance of this system, with efficiency higher than 50% while providing finite ergotropy. To illustrate how one can fabricate our device, we report a feasible scheme for a superconducting quantum battery based on three dc-SQUIDs weakly coupled to a thermal bath, which is responsible for the initialization of the battery's state. This part is followed by numerical simulations on the IBM quantum computer. Although the errors affected the net performance, the results agree with the initial theoretical proposal. Thus, our research provides a wide range of new directions for developing quantum batteries and quantum computing.

Quantum Information Engine Revised: Measurement Time, Time-dependent Information Acquisition, Energy Cost, and Performance

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Measuring the state of a quantum system and gathering information about it is a foundational operation applicable in various fields, from quantum computing for determining qubit states to quantum chemistry for discerning states in reaction pathways. While a measurement typically alters the original quantum state, the information obtained can be harnessed to drive processes and, from a thermodynamic standpoint, enhance energy transduction to useful work. One crucial aspect of these measurement processes is the time required to acquire information and the associated energy costs, which are usually overlooked. These considerations, however, are vital for developing more efficient quantum devices that can gather optimal information while minimizing energy resources per measurement time. The following Figure 1 illustrates an exemplary energy transduction process which is administered by time-dependent measurement.

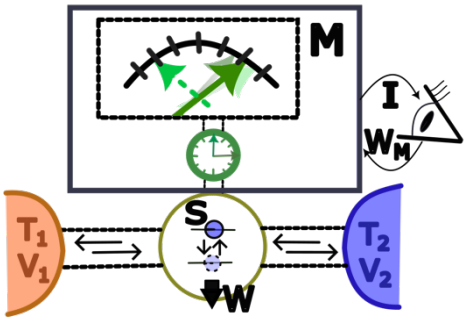

*Figure 1: Measuring the transfer through a quantum system S coupled to two reservoirs of different temperature T and potential V where the transport is measured by a measurement device M. The system is **time-dependently** coupled to a measurement device which will be read out to obtain information **I** about the system which comes with a cost of measuring W_M while useful work **W** can be extracted from S.*

In this context, we revise a prototype non-autonomous information engine 'powered' by an external observer, commonly known as Maxwell's demon. By observing the system's state, Maxwell's demon enables the extraction of useful work from a single heat source. Previous studies on such engines have discussed information gain without considering the time and energy required to obtain information, assuming that the demon can acquire information instantaneously at no additional energy cost except for memory erasure to a heat bath.

Our research[1] addresses these issues by studying a two-level system interacting with a quantum free particle as a meter. We use the two-step Von Neumann measurement protocol to analyze two key aspects separately: (i) the evolution of the coupled system and meter, the entanglement between them as functions of the coupling and its duration, and the information gained in this process, and (ii) the fundamental energetic costs associated with coupling and decoupling the system and meter. This approach allows us to consider the energetic cost of acquiring information. Additionally, by incorporating photon-induced stimulated emission in the protocol, we investigate work extraction driven by information obtained from the measured system. Our analysis focuses on the ratio between the work generated from acquiring information and the energy required to obtain it, as well as the power output (energy per measurement duration) and its optimization.

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Optimizing Energetic Efficiency in Silicon Spin Qubit Quantum Devices

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The excitement surrounding quantum computing and its potential for fast and efficient calculations faces the reality of multiple engineering challenges and limited physical resources. While multiple platforms have demonstrated high performing qubits at small scale, noise and increasing cooling costs limit the performance of intermediate and large scale quantum devices [1, 2]. Exploring the nature of these limitations has the potential to unveil hidden inefficiencies in design or experimental settings that could steer researchers towards practical optimisation. To benefit from the intrinsic relationship between resource cost and success of computation, a model relating noise to physical and computation variables is necessary [3]. To this end, we present a full-stack model of a quantum computer based on experimental data from the silicon spin qubit platform.

In particular, we investigate two types of spin qubits in silicon, the electric dipole spin resonance (EDSR) and the electron spin resonance (ESR), each coupled to an electric or magnetic field, respectively [4, 5]. In this study, we relate microscopic variables such as the duration of a single qubit gate to macroscopic variables like the power consumption of the cryostat. Their connection is established through a noise model based on current technological capabilities and realistic experimental settings. To achieve a full-stack approach, energetics of individual gates, qubit measurement, heat conduction of the cables as well as cryogenic power is all taken into account and related to the fidelity of the computation. To compare the energetic efficiency of the two spin qubit platforms we estimate their energy consumption for the implementation of 4-qubit variational quantum eigensolver (VQE) algorithm and a 20-qubit random benchmarking circuit. Finally, using the Metric-Noise-Resource (MNR) methodology, we optimise the power consumption of the two set-ups to discover optimal qubit temperature and driving frequency as a function of the success of the computation.

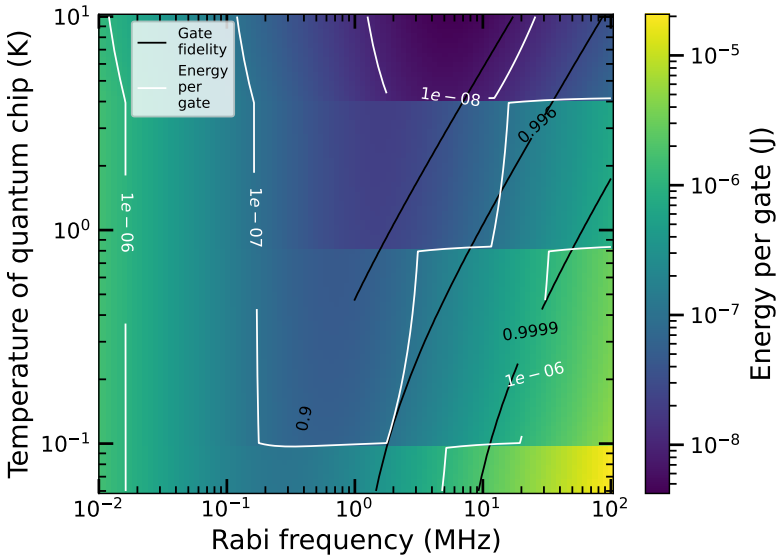

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Fig. 1. Energy consumed by a single-qubit gate in Joules (with cryogenics at Carnot efficiency), as a function of Rabi frequency and qubit temperature. Black contour lines mark the gate fidelity while white contour lines guide energy profile. The optimal temperature for each fidelity can be traced at the darkest areas.

Measurement of the Lindbladian of quantum computers with randomized Pauli measurements

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In this work we propose a scalable Lindbladian (Hamiltonian and dissipation) measurement protocol for multi-qubits systems. Having a generic characterization protocol of the Lindbladian, i.e. practicable on large systems and without strong assumptions about its form, is crucial for certifying the dynamics of quantum computers. For example we want to be able to detect and then potentially correct unwanted terms in the qubit dynamics. Theoretical proposals have been made to tackle this exponential scaling problem with the system size but there is little experimental demonstration.

We have studied how the protocol described in Daniel Stilck França's article entitled ”Efficient and robust estimation of many-qubit Hamiltonian"[1], can be implemented with randomized Pauli measurements. We will illustrate its practicality using experimental data from a 10 qubit system with a two body Hamiltonian and local dissipation.

In this work we will assume that the qubits are subject to a Markovian quantum evolution, described by a time-independent Lindbladian. The method is applicable to any qubit architecture. The only device requirements are to be able to initialize and measure the qubits in random Pauli states and bases. The randomness of the protocol allows massive parallelization of the measurements and an efficient reconstruction of the expected values of all the one and two body Pauli observables from the N-qubit measurements [2]. The the t=0 derivatives of the observables are then extracted from the data and the Lindbladian coefficients can be learned with a closed system of equations on each qubit pair.

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QUANTUM MULTI-TIME PROCESSES IN CONTINUOUS VARIABLE SYSTEMS

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Quantum multi-time processes are general quantum processes that occur in a span of time, and which may be interacted with at several time intervals. These processes may, in general, be non-Markovian, whereby temporal correlations arise from interaction of the system with some typically inaccessible environment, giving rise to noise [1, 2]. To use a Markovian process to model these would be to ignore temporal correlations and lose out on valuable information that may be useful in error mitigation.

Therefore, one such way to characterize these multi-time non-Markovian processes are quantum combs. They describe coupled unknown environment and system transformations in practical terms by characterizing these transformations in terms of initial preparations, final output and intermediate measurement outcomes at each time step [1, 2] — information that is typically accessible to an experimental set-up. While this framework has been developed in discrete variable systems, it lacks a continuous variable counterpart. However, understanding of non-Markovianity in continuous variables is crucial, given its relevance to practical, experimental set-ups and other technologies like reservoir computing [3, 4].

We thus extend the framework of quantum combs to general continuous variable systems by developing an analogous description, before elucidating the characterization, key properties, and relative entropy as a non-Markovianity measure of Gaussian quantum combs due to their potential relevance in experimental optical systems.

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Modeling the Quantum Spintronic Engine

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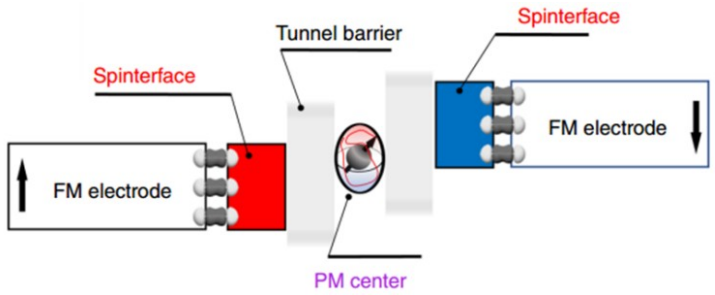
Quantum heat engines have attracted extensive research as they give us a glimpse of abundant, continuous, dense, microscopic and environmentally friendly power sources. Recent theory and experimentation have showcased how to use quantum features in order to harvest thermal energy stored as quantum heat and convert it into usable work but, so far, this has required cumbersome external energy sources, therefore nullifying their potential use cases.

Our team has proposed a spintronic implementation of such an engine that can operate autonomously by rectifying the quantum fluctuations of a spin chain trapped inside a ferromagnetic tunnel junction (see Figure 1) [1]. We will describe additional experiments, in which the spin chain is borne by the Co paramagnetic centers of phthalocyanine molecules, and is maintained in a coherent superposition of states thanks to electron-spin selecting Fe/C60 interfaces [2]. This generates a spontaneous current across several molecular nanodevices.

To explain these results, we will introduce the spintronic engine and give insight towards its quantum description in terms of transport, spin, thermodynamics and quantum resources. An overview on the magneto-transport experimental results will be shown and then we will give a description of the three theoretical models under study, which aim at explaining the spontaneous current generation we observe in our device [3].

A first microscopic quantum description relies on the energy provided by autonomous measurement back-action: the operation of the engine is split into two strokes: a thermalizing stroke that releases electrical work into the bath thanks to the relaxation of the system, followed by a measurement stroke that energizes the system by killing the entanglement present in the steady-state [3]. The second mesoscopic and approach models the device as a nonlinear spintronic material that produces work thanks to a spin potential maintained thanks to the interface and the magnetization difference between the two electrodes. And the third macroscopic model considers the device at the electronic circuit level and proves the power generation thanks to a spin diode effect rectifying the spin population imbalance.



	Source	Typ. Pd (mW/cm²)	Constraint
Natural	Paramagnetic fluctuators in a MTJ	30000	R&D / Engineering...
Artificial	Solar	50	Not 24/7
	Thermoelectric	30	T gradient
	RF power	1	Distance/ Harmonics
	Vibration/PZT	0.2	Vibration frequency
	Vibration/EM	10	AC/DC conversion

Figure 1: Schematic of the spintronic engine (left) and table comparing the power densities of conventional energy harvesters with our engine (right) [1]

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3. Mathieu Lamblin and Martin Bowen. Quantum measurement spintronic engine powered by quantum coherence enhanced by bosonic catalysis. *Phys. Rev. B* **109**, 165423 (2024).

Optimizing shotrcut-to-adiabaticity with respect to thermodynamic costs

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The family of protocols referred to as shortcut-to-adiabaticity (STA), initially imagined for quantum thermodynamic operations like in cyclic quantum engines, are now also used in operations related to quantum information processing, and experimentally applied in many quantum platforms (cold atoms, NV centers, trapped ions, superconducting circuits, and atoms in cavities). One of the main appealing features of STA is to maintain throughout the dynamics the system in the same level of excitation. For thermodynamic operations, the other interesting characteristic is that STA protocols minimize the work expenditure (at least for quantum systems initially in passive states).

However, the energy invested to generated the STA control, that we refer to as thermodynamic costs, remains uncontrolled, and became a major concern in recent investigations. Using a recent proposal for a physically motivated figure of merit for such thermodynamic cost [1], we explore possible alternative protocols realizing the same overall operation as traditional STA protocols, but designed to minimized such thermodynamic costs. The minimization is performed using techniques from Optimal Control Theory adapted to quantum systems (namely the Pontryagin Maximal Principle). As illustrative application, we consider a two-level system, and we show that our suggested protocols can reduce significantly the thermodynamic costs. Perspectives include extending such study to other platforms and practical experimental situations, as well as considering the minimization of fluctuations.

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COMBINING ENERGY EFFICIENCY AND QUANTUM ADVANTAGE IN CYCLIC MACHINES

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Energy efficiency and quantum advantage are two important features of quantum devices. I will report on the first experimental realization that combines both features in a quantum engine coupled to a quantum battery that stores the produced work, using a single ion in a linear Paul trap. I will begin by establishing the quantum nature of the device by observing nonclassical work oscillations with the number of cycles as verified by energy measurements of the battery. Applying powerful shortcut-to-adiabaticity techniques that reduce nonadiabatic transitions, quantum friction was moreover effectively suppressed, improving work production. While the average energy cost of the shortcut protocol is only about 3%, the work output is enhanced by up to approximately 33%, making the machine significantly more energy efficient. I will additionally show that the quantum engine consistently outperforms its classical counterpart in this regime, indicating quantum advantage. These results pave the way for energy efficient machines with quantum-enhanced performance.

Reference:

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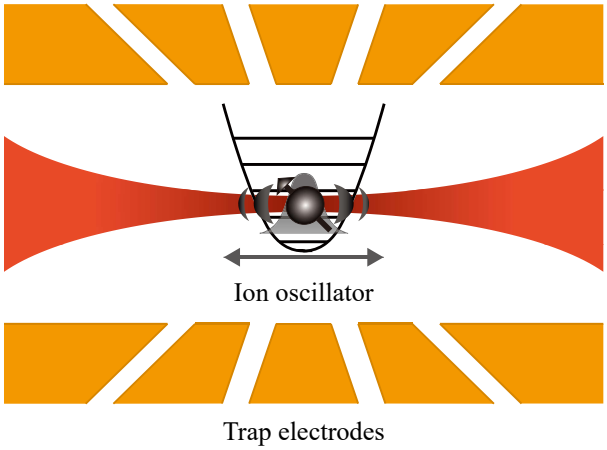

Quantum Chaos and Dual Unitary Systems: Pushing the Boundaries of Science with Quantum Computers

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Quantum computers are unlocking possibilities in science that were once thought beyond reach. While we are still exploring the full potential of these remarkable machines, their power is already helping to push the boundaries of what we know—and bringing tangible benefits to science and humanity.

In a joint study led by Algorithmiq, in collaboration with Trinity College Dublin and IBM Quantum, we use quantum computers to explores the behavior of quantum systems that exhibit chaotic dynamics [1]. This field is essential for understanding complex systems, the spread of information, and thermalization, with impacts on quantum computing, condensed matter physics, and even astrophysics.

Recently, dual unitary (DU) systems have garnered attention as rare, exactly solvable models that exhibit maximum chaos. These systems are "dual" because their unitarity holds in both time and space, allowing for the analytical computation of typically intractable properties, such as correlation functions. DU circuits serve as exceptional benchmarks for quantum simulations, helping us study critical phenomena like quantum scrambling, entanglement growth, and the decay of correlations—all fundamental to quantum chaos and many-body physics. Their analytic tractability also aids in designing and testing quantum algorithms for real-world applications.

In this talk, I will present how we leverage our own state-of-the-art error mitigation techniques (TEM) [2] to simulate the decay of auto-correlation functions in quantum chaotic many-body systems. These functions are vital for understanding transport properties, such as conductivity and diffusion, and for addressing fundamental questions in non-equilibrium quantum dynamics.

Our simulations achieved unprecedented accuracy on a cloud-based 127-qubit Eagle processor, using up to 91 active qubits and 91 entangling gate layers, amounting to over 60,000 gates and about 4,100 CNOT gates. This marks the largest-scale digital simulation of correlation functions in an interacting quantum many-body system to date. This breakthrough demonstrates that we can already benefit from this technology by advancing scientific understanding today.

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Energy efficiency of quantum neuromorphic computing

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The brain achieves remarkable energy efficiency, consuming orders of magnitude less power than digital computers, thanks to its distributed architecture and reliance on analog signals. Classical neuromorphic computing emulates this architecture in hardware to reduce energy consumption. By leveraging analog signals, it exploits phenomena like synchronization for computation and employs frequency, amplitude, and phase modulation for data encoding.

Quantum neuromorphic computing extends these principles into the quantum realm, utilizing analog quantum systems and their intrinsic dynamics for information processing and feature embedding. Nonlinear feature extraction, essential for neural processing, can be achieved through various measurement schemes, including expectation values of observables such as average occupations[1], field quadratures with Kerr nonlinearity[2], and Fock basis projections[3]. We have recently shown that the time evolution of quantum systems can be trained by optimizing drive and interaction Hamiltonian parameters[4]. This enables to evolve the system to states where measurement outcomes yield features that can be linearly combined to perform diverse classical tasks.

An important question arises: can quantum neuromorphic computing deliver energy advantages similar to those observed in classical neuromorphic systems? A promising perspective is its application to quantum tasks. Once trained, quantum neural networks have the potential to perform tasks on quantum data with greater energy and time efficiency. For instance, they could be used to recognize specific quantum states in a single measurement shot—achieving a feat that would otherwise require millions of shots for complete quantum state tomography.

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ANOMALOUS DISCHARGING OF QUANTUM BATTERIES: THE ERGOTROPIC MPEMBA EFFECT

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Understanding how to efficiently extract energy from a quantum source is a cornerstone for the development of new technologies. Over the last decades, the field of quantum thermodynamics provided us some fundamental tools to explore how quantum features play a role in this task and whether or not quantum advantages can be obtained. A promising quantum device to achieve these tasks is the so-called Quantum Battery (QB), which has been firstly proposed by R. Alicki and M. Fannes [1]. The idea of a QB is to harness intrinsic quantum phenomena, such as entanglement and coherence, in order to efficiently store and release energy on demand. In general, the main figure of merit to characterize the efficiency of the QB is the *ergotropy* [2], which is the maximum work that can be extracted from a quantum system by means of cyclic unitary operations. This quantity can be understood as the total amount of energy the QB can store.

Although QBs have been on the spotlight in the last decade and many protocols have been proposed [3], there are still challenges to overcome in order to implement real batteries. For instance, the interaction with an environment will cause the charge stored in the QB to be depleted. Then, find realistic protocols to stabilize or slow down the process of energy loss in the QB is an important topic of research.

In this work, we are going to discuss how a single bosonic mode can be used as a Quantum Battery. We assume that our system is restricted to the important class of Gaussian states, which are completely characterized by a mean vector of first moments and a covariance matrix of the second moments. We show that the *ergotropy* can be written as the Wigner relative entropy between the state and its passive. Also, we show that the passive state is a thermal state with temperature that is obtained from the covariance matrix of the state we want to extract energy. Moreover, we discuss how the *ergotropy* can be split into two independent contributions that depend on the displacement and squeezing operations. Finally, we show that when our system interacts with an environment, there are certain states that have initially more ergotropy, but that discharge faster than other states that have less ergotropy, given rise to a Mpemba-like effect on the ergotropy.

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Autonomous Quantum Processing Unit: What does it take to construct a self-contained model for quantum computation?

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(Dated: October 3, 2024)

Computation is an input-output process, where a program encoding a problem to be solved is inserted into a machine that outputs a solution. For classical computation these processes are conventionally modeled using Turing machines, a formalism that has been lifted into the quantum domain by Benioff [1], Feynman [2] and others. This approach has been exceedingly successful in defining computational complexity for quantum computers.

When it comes to the real-world cost of computation, however, the energy a computer consumes to run an algorithm becomes a critical quantity of interest that is not solely captured by computational complexity. While many foundational works in the past have investigated the energetics of quantum processes, they have often done so under idealizing assumptions. These neglect that in practice the macroscopic systems needed for controlling quantum processes dominate the energy requirements by a quantum computer. Some recent works have successfully explored the energetic cost of computation from the applied perspective [3], which relies on certain heuristics to quantify the cost of control. This raises the foundational question of whether a fully self-contained model for quantum computation can realistically include classical control in its description. We answer affirmatively with the autonomous quantum processing unit (aQPU), which integrates control into the mathematical framework and rigorously defines the resources consumed during computation (see Fig. 1). By focusing on energetic resources, we extend beyond prior work on abstract quantum Turing machines, establishing a basic framework for classifying the energetic cost of computation, much like Turing machines have done for computational complexity.

For experts [4]. The aQPU is based on an open quantum system model using a quantum master clock to time the elementary gates of the algorithm that is run. The energetic cost is quantified with the entropy production Σ, which we find to be a crucial factor when determining the computational fidelity $\mathcal{F}$. For dissipative clocks, the two are related with $(1-\mathcal{F}) \sim 1/\Sigma$ and quantum clocks can improve the right-hand, to e.g., $1/\Sigma^2$.

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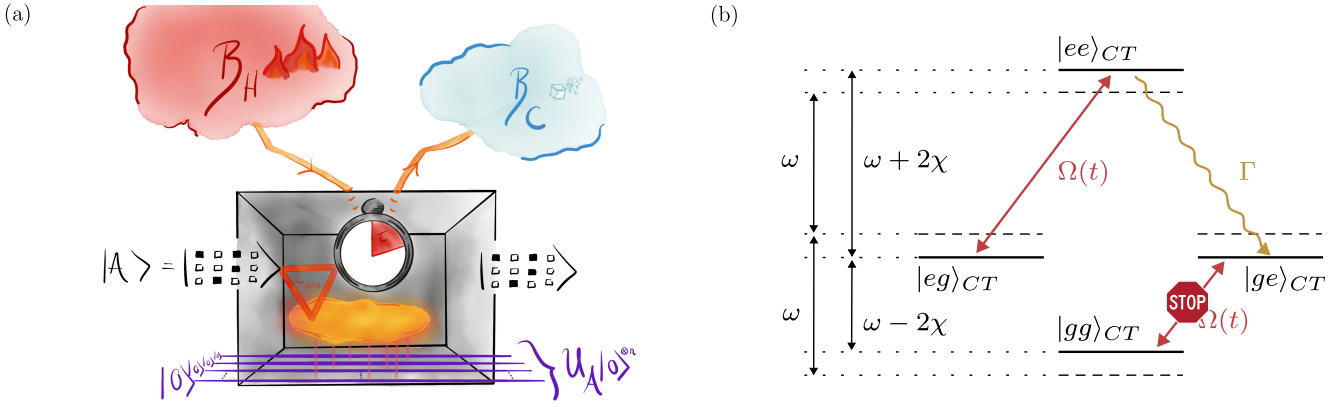

FIG. 1. (a) A qualitative sketch of the autonomous quantum processing unit (aQPU) taking quantum input and autonomously computing its output using out-of-equilibrium baths. Conceptually, such a mechine can be driven by a voltage or temperature gradient as sketched in the figure. (b) An energy-level diagram of a minimal spin-spin system whose dispersive interactions could serve as a building block to realize the autonomous control.

Quantum Computing Energetics: The point of View of an HPC user

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Towards quantum advantage with photonic state injection — Extended abstract

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(Dated: October 4, 2024)

While photonics is one of the promising platforms for building a fault tolerant quantum computer, the technological requirements for such devices are huge. They often rely on the capacity to achieve adaptive measurement-based operations and on the access to a large number of modes and initial coherent photons [1]. In that regard, sub-universal models have been proposed to achieve near-term quantum advantage [2, 3]. Finding an architecture able to offer a quantum utility to real life use case for quantum photonic device in the era of Noisy Intermediate-Scale Quantum devices is an important field of research. Quantum Machine Learning (QML) is a promising field of application for photonic platforms that requires to go beyond linear optic architectures to increase the expressivity of the resulting models. Previous works came up with alternative solutions to incorporate non-linearity — an important element for neural network architectures — such as global measurements and classical activation functions between linear optical layers [4], physical non-linear blocs [5], or adaptive gates to perform learning tasks [6].

In this work, we introduce the State Injection scheme. We study the use of linear optical layers interleaved with state injection (SI), a measurement-based channel that does not require gate adaptivity throughout the computation, but rather the preparation and injection in the circuit of new quantum optical state. It is motivated first by experimental consideration. The main challenge of adaptive architectures, i.e., those relying unitary parameterized by measurement outcomes, is the waiting time to reprogram the chip after measurement. Such schemes requires delays (or quantum memories) between the unitaries that are in the order of milliseconds, equivalent to few hundreds of kilometers of fibers which will have more losses and harder synchronization. On the contrary, State Injection relieves the need of the real time adaptability of the consequent unitaries. Instead, it relies on active real-time Fock state preparation to replace the few measured modes depending on their measurement outcome and synchronizing the new states with the unmeasured modes of each unitary, using mainly external (to the unitary) fast optical switches which reduces the delay required for the non measured modes. Average commercial switches relying on micro or nano electro-optical technologies [7, 8] can work in microseconds range which reduces the optical delay to the order of few hundreds meters.

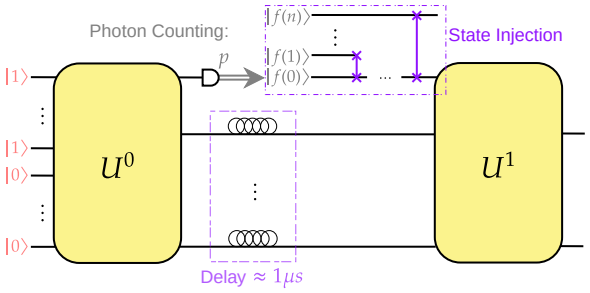

FIG. 1. Building block of the state injection architecture. The occupancy of first output mode of U^0 is measured, yielding p, from what a new Fock state $|f(p)\rangle$ is created and injected in the first input mode of U^1.

This scheme allows to increase the expressivity of the photonic quantum circuits and to perform tasks that are believed hard to do classically with fewer experimental constraints in comparison with the Adaptive Linear Optics scheme [6]. More precisely, we show that the scheme we introduce offers three improvements upon state-of-the-art linear optical quantum machine learning techniques. First, as the scheme goes beyond linear optics, the circuits do not suffer from the controllability limitation inherent to Boson Sampling. Second, consider non-unitary channels increase the controllability at the cost decreasing the purity of the state, we provide bounds on the purity evolution of the state which allows one to design an architecture to precisely trade off controllability for purity. Third, we support the use of the architecture for quantum machine learning purposes by arguing why output probability amplitudes are likely to be hard to estimate classically up to inverse-polynomial precision in polynomial time. State injection could also be used to design so-called subspace-preserving circuits [9], as the suitable injection function preserves the total number of involved particles.

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AUTONOMOUS DEMON EXPLOITING HEAT AND INFORMATION AT THE TRAJECTORY LEVEL

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In nanoscale devices, heat generation is unavoidable due to, e.g. dissipative processes, and it is problematic as it is detrimental to quantum effects and increases energy consumption. Heat management, including cooling directly on chip, is therefore an important question for quantum technologies. Being at the nanoscale gives access not only to heat, like in usual heat engines, but also to other resources such as ***information***, like in Maxwell demon-based engines, or as ***nonthermal fluctuations.*** Since fluctuations can be sizeable, precision, namely how noisy the output power is, is a key performance quantifier for such devices. Here, we study a refrigerator-type device based on thermoelectrics which generates a heat flow from cold to hot in the working substance ***in the absence of any average particle or energy flow*** from the resource region (thereby acting as a "demon"). Analyzing the microscopic processes gives us insight into the respective roles of heat and information exchanges in the cooling process and the refrigerator's performances in different regimes.

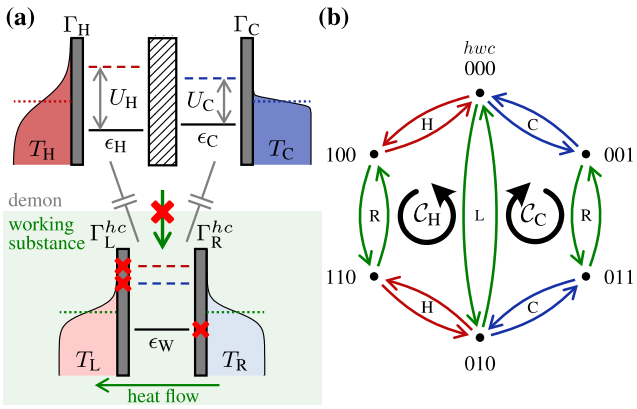

Fig. 1: (a) Setup: three capacitively coupled quantum dots coupled to electronic reservoirs at different temperatures. The lower half (green) is the working substance, while the upper half (white) emulates a nonthermal distribution and corresponds to the demon. The aim is to transfer heat from the colder right reservoir into the hotter left reservoir without average energy transfer from the demon.
(b) Diagram of the possible transitions between the different states hwc of the three dots where h,w,c = 0,1 indicate the number of electrons in each dot. The black arrows represent the two fundamental cycles involving only one demon reservoir which we use to decompose all steady-state flows in the device.

Specifically, we study a three-quantum-dot setup in which one dot is coupled to two electronic reservoirs at different temperatures (the working substance) while the other two dots are respectively in contact with a hot and a cold reservoir (the demonic resource), see Fig. 1(a). Here, the capacitive coupling between the dots creates an autonomous feedback mechanism that can participate in reversing the heat flow from cold to hot in the working substance and be interpreted as an autonomous Maxwell demon scheme. With a stochastic trajectory approach, see Fig. 1(b), we characterize the contributions of the hot and cold demon reservoirs to the heat and information exchanges. We then leverage this analysis to understand the performances of this refrigerator, in particular the precision of the cooling process. We identify two operation regimes yielding similar cooling powers and efficiencies but very different precisions. The first is mostly information-focused and the hot demon reservoir is mostly used to cancel out the average heat flow, leading to poor precision. Conversely, in the second, only the interaction with the cold reservoir exploits information but both demon reservoirs contribute positively to the cooling, leading to much better precision [1].

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GENERATION OF AUTONOMOUS QUANTUM RESOURCES BY DISSIPATIVE QUANTUM SYSTEMS

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Theory of open quantum systems, i.e., systems coupled to thermal bath(s) in the quantum regime [1] despite of its age still constitutes a vivid research field addressing various aspects of the general question how the dissipative coupling to a bath, which inevitably also brings quantum noise, influences the quantum dynamics of the studied system. The question is particularly important in the context of quantum information setups where quantum resources such as coherence or entanglement should be prevented from the (supposedly) detrimental effects of the noise. However, as it has turned out recently, the sole dissipative coupling of a quantum systems without any further external control (such as driving fields) can, in fact, also be used for *generation* of such quantum resources, which are then called *autonomous*. Our poster addresses two complementary situations for generation of quantum resources – autonomous coherence generated by coupling to an equilibrium quantum bath [2,3] and generation of autonomous quantum entanglement in a nonequilibrium setup [4].

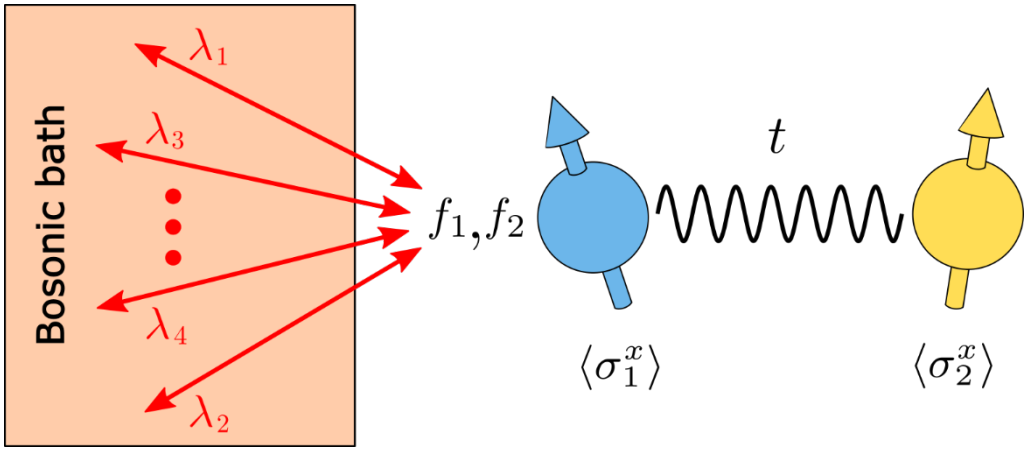

Figure: Setup for extracting autonomous quantum coherence (from Ref. [3a]).

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Dynamic Cooling of Qubits on Contemporary Quantum Computers

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A key hurdle for the success of quantum computers is the ability to prepare pure (i.e., cold) qubits. Dynamic cooling, which was first proposed over two decades ago, offers a route to effectively lower qubit temperatures beyond what is possible with direct, physical cooling techniques using e.g., lasers or large magnetic fields. It works by cooling a subset of qubits, at the expense of heating others, by applying certain logic gates to the entire system. However, it exhibits poor scaling with system size in the high initial temperature regime; since qubits in the NMR-based quantum computers available at the time of its inception were initialized at effectively high temperatures, dynamic cooling was dismissed as ineffectual and essentially abandoned.

Here we reexamine dynamic cooling in light of the development of quantum computers that operate at very low temperatures. Our analysis reveals a crossover from the high initial temperature regime to the low initial temperature regime, in which scaling becomes much more favorable. We further show that the associated work cost of cooling is exponentially more advantageous in the low-temperature regime.

Given this theoretically favorable performance of dynamic cooling, we turn to examining its implementation on quantum computers. We study the effect of hardware noise on cooling and find that the apparent exponential growth of circuit-size with the system size significantly hampers performance. To address this, we propose a sub-optimal dynamic cooling scheme with fixed (low) circuit complexity to improve the feasibility of implementation on noisy quantum hardware. Finally, we show a successful execution of dynamic cooling with a 3-qubit system on a real quantum processor.

The problem of cooling qubits is essentially a problem of moving energy in an advantageous manner. A better understanding of moving energy from the computational qubit to other parts of the system or out into the environment, will aid in improving the cooling a qubits, which in turn will improve the performance of quantum computation.

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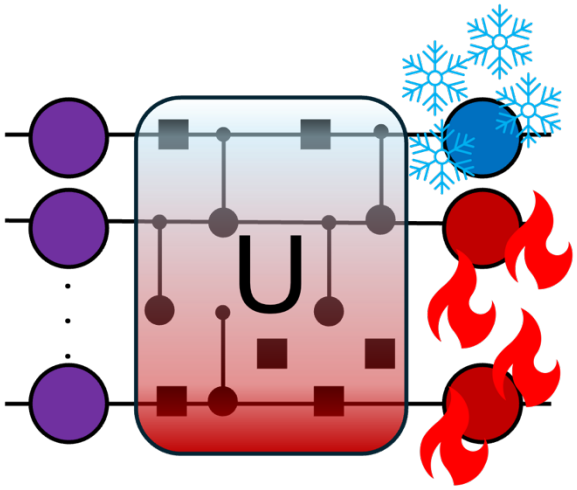

Energetics of Quantum Computation

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Superconducting circuits as a platform for quantum thermodynamics experiments

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Superconducting quantum circuits and superconductor-normal hybrids provide a highly controllable testbed for open quantum system and quantum thermodynamics experiments. Heat baths are formed of metallic reservoirs which can be coupled to the quantum systems and whose temperature can be controlled and measured in situ.
In this talk I review our experiments performed over the past few years on these platforms. I will pay particular attention to pure quantum features in these and future experiments, e.g., to the role of phase coherence in thermal phenomena, and to applications of the platforms in ultrasensitive bolometry and calorimetry.

Optimizing NISQ computers (QEI2025)

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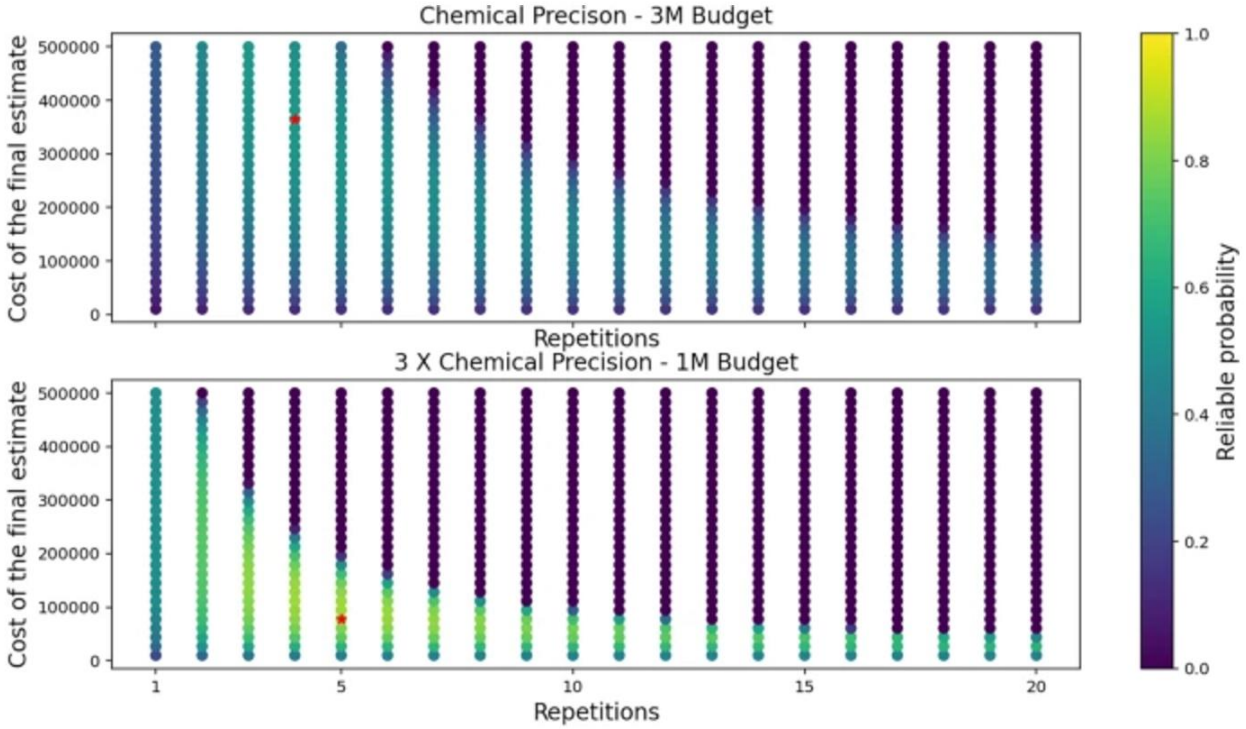
The current state of quantum computing is commonly described as the Noisy Intermediate-Scale Quantum era. Available computers contain a few dozens of qubits and can perform a few dozens of operations before the inevitable noise erases all information encoded in the calculation. Even if the technology advances fast within the next years, any use of quantum computers will be limited to short and simple tasks, serving as subroutines of more complex classical procedures. Even for these applications the resource efficiency, measured in the number of quantum computer runs, will be a key parameter.

Here we suggest a general meta-optimization procedure for hybrid quantum-classical algorithms that allows finding the optimal approach with limited quantum resources. This method optimizes the usage of resources of an existing method by testing its capabilities and setting the optimal resource utilization. We demonstrate this procedure on a specific example of variational quantum algorithm used to find the ground state energy of a hydrogen molecule.

On the graph below, we show how the probability of obtaining a reliably good result within a desired precision (in multiples of Chemical precision) depends on the “budget” of shots – number of runs of the quantum computer giving a discrete measurement result. To achieve this probability, our optimization suggests how to mix the number of repetitions of the optimization procedure (as it is stochastic, it might fail) and the budget for final estimation (large number of computer runs is needed to correctly estimate the value of the optimum found and thus correctly choose the best result). The red point shows the best achievable probability, reached for different number of repetitions for different desired precision and total budget. It is interesting to see that for one repetition of the optimization, as usually used, the results are far from being optimal.



ENHANCEMENT IN ENERGY STORAGE PRECISION USING NON-GAUSSIAN QUANTUM BATTERIES

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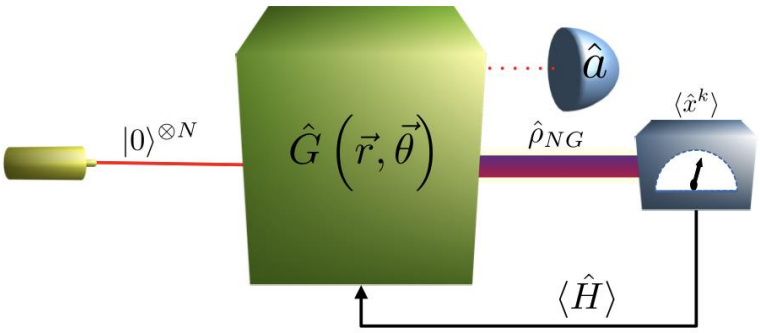
Quantum states of light possess unique properties that make them exceptional carriers of information, positioning photonic circuits as a highly promising platform for quantum simulation. In this work, we present our findings on the variational optimization of energy storage devices, specifically quantum batteries, using a photonic-inspired quantum neural network architecture:



Our approach leverages the continuous-variable (CV) framework for quantum information, which offers significant advantages for quantum simulation of continuous systems, like quantum fields. By encoding information in the quadratures of the electromagnetic field modes, this framework allows for the representation of infinite-dimensional degrees of freedom without truncation in the Hilbert space.

A quantum battery is an infinite-dimensional bosonic system of N modes, whose dynamics are governed by the harmonic oscillator Hamiltonian, such that by performing unitary operations on an initial passive state, one can prepare the system in an excited state, increasing its energy by some quantity known as *ergotropy*, which is stored in the system and will be later available for extraction.

We argue that the potential quantum advantage in this context comes from optimizing energy storage *precision,* making these devices suitable for accuracy-demanding nanotechnological tasks. For this reason, we consider as our figure of merit the ratio between the extractable energy and the error in the knowledge of such energy, and we perform a variational optimization though our QONN algorithm to maximize it. Our results show that there exists an upper bound to the optimal performance of Gaussian batteries, while the introduction of non-Gaussianity into the system by applying single-photon subtractions or additions to an initially Gaussian state allows for the violation of such bound and gives a significant gain in terms of storage precision, which in turn becomes more noticeable as the degree of non-Gaussianity increases.

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Quantum thermodynamics of continuous feedback control (QEI2025)

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The laws of thermodynamics are the cornerstone of describing nanoscale and open quantum systems in the frameworks of stochastic and quantum thermodynamics, which describe fluctuations in these systems [1]. However, formulating the laws of thermodynamics for systems under continuous feedback control and under experimentally relevant conditions is challenging.

In this work, we fill this gap by investigating the laws of thermodynamics for an open quantum system under continuous measurement and arbitrary feedback scheme described by a Quantum Fokker Planck Master Equation [2], where the detector implementing the feedback has a finite bandwidth, which is experimentally realistic condition [3].

We derive expressions for work, heat, and measurement-induced energy change, which is a genuinely quantum effect originating from coherent effects during the measurement. Further, we investigate entropy production and fluctuation theorems, which describe irreversibility in the system's dynamics.

We illustrate our results with a continuous version of a measurement-driven Szilard engine [4], where the measurement-induced energy changes are used to fuel work extraction. Furthermore, we use our results to analyze a work extraction scheme in a two-level system under a bang-bang control, which is a nonlinear threshold-like feedback scheme.

Our research provides a novel characterization of the laws of thermodynamics for classical and quantum systems under continuous feedback control and experimentally relevant conditions, thus leading to a deeper understanding of thermodynamics in nanoscale and quantum regimes.

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Thermoelectric spectroscopy for *in situ* characterisation of nanodevices

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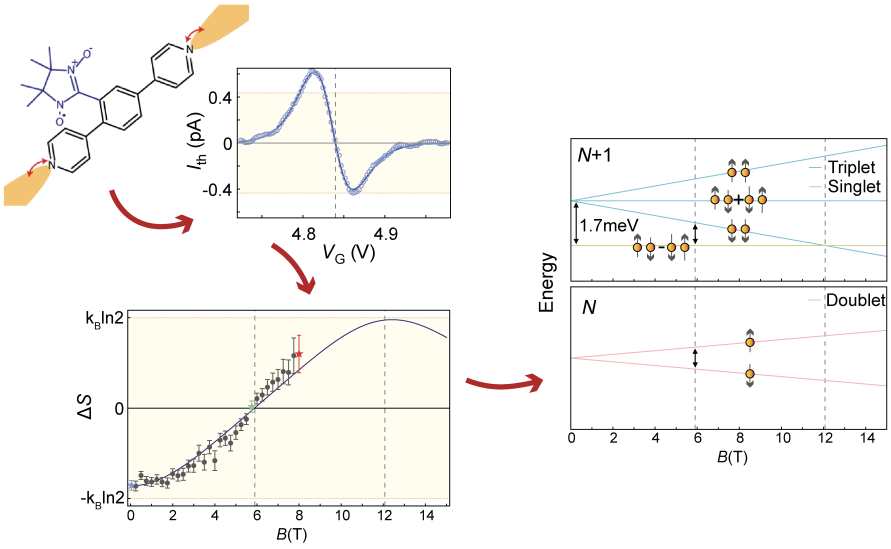

Figure 1: Entropy difference between charge states can be extracted from fitting the thermoelectric signature of a quantum nanodevice. The value of entropy, in turn, allows to deduce the microscopic dynamics of the system, such as the energy level structure.

It can hardly be disputed that the next stage in the trend for miniaturisation of technology is harnessing quantum effects. It has been shown that engineering quantum features, such as tunnel couplings or interference paths can lead to unprecedentedly high energy harvesting efficiencies[1], or greatly reduce the passive energy consumption of nanoscale transistors[2].
However, a major obstacle on this path is post-fabrication characterisation. In order to guide the intelligent design of nanodevices for improvements in efficiency or the on/off current ratio, we need a way to not just measure these macroscopic parameters of interest, but also directly probe the internal quantum dynamics that led to them. This is an experimental challenge lying outside of the capabilities of standard characterisation techniques, such as microscopy or spectroscopy.
As a possible solution, we propose a method we call “thermoelectric spectroscopy”. We use an experimental technique that allows for simultaneous measurement of current, thermocurrent and differential conductance of an electronic nanodevice[3] and show that this combination of data can shed a lot of light into the quantum states present in the device.
We demonstrate the application of the method to exploring the structure-property relations in quantum nanodevices, show that it allows to directly obtain the entropy difference between charge states of a single-molecule nanodevice and in some cases to fully determine the energy level structure of the molecule in situ in a solid-state device in a fully assumption-free manner[4], and also discuss the limitations of the method.

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Advantage in quantum batteries: the role of energy fluctuations

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Classical batteries are systems that can store energy after being charged, and eventually deliver it on demand. If the employed systems are nanoscale devices, such as superconducting qubits or quantum dots, these are called *quantum batteries* [1]. Despite the increasingly growing interest around these devices [2], nowadays their importance lies in the fact that they lend themselves to being described by a thermodynamic point of view, hence favoring the study of energy exchanges and, most of all, their fluctuations [3] in the framework of quantum statistical theory. In fact, the more the dimensions of the devices are reduced to the nanoscale, the smaller the energy quantities to be stored, and the more the amplitude of fluctuations is comparable to them. In any realistic usage of quantum technologies, e.g., for an efficient quantum computation, it is necessary to limit fluctuations in order to reduce the presence of noise (e.g., via error correction techniques). Besides, a better knowledge of fluctuations allows also to individuate the less-fluctuating processes, thus indicating a preferable route towards the development of more precise quantum devices and the optimization of quantum technologies.

In our work [4], we studied a Jaynes-Cummings quantum battery (JCQB), i.e. a battery consisting of a flying qubit interacting with an optical resonator (see schematic illustration in Figure 1a). By employing the Full Counting Statistics [3], we analytically found that it is possible to enhance the charging performance of the battery by preparing the single-mode resonator in a genuine quantum state. In fact, if the cavity mode is initialized in a Fock state $|N\rangle\langle N|$, the charging process is more efficient than the "classical" counterparts (e.g., protocols involving a cavity in a squeezed coherent state). Most of all, we show that this quantum advantage is *reliable*, since we take into account the dynamical energy fluctuations occurring during the process. We indeed prove that the advantage still persists in the case of Fock state cavity: this can be seen by evaluating the signal-to-noise ratio (SNR) shown in Figure 1b, which quantifies how good is the signal (the average energy injected into the battery) with respect to its fluctuation (the variance). This result suggests that understanding the dynamics of fluctuations in quantum batteries is of paramount importance, since the same advantage that can emerge from these models could be exploited to refine the efficiency of quantum technologies, by analysing the energy fluctuations that take place in their core processes.

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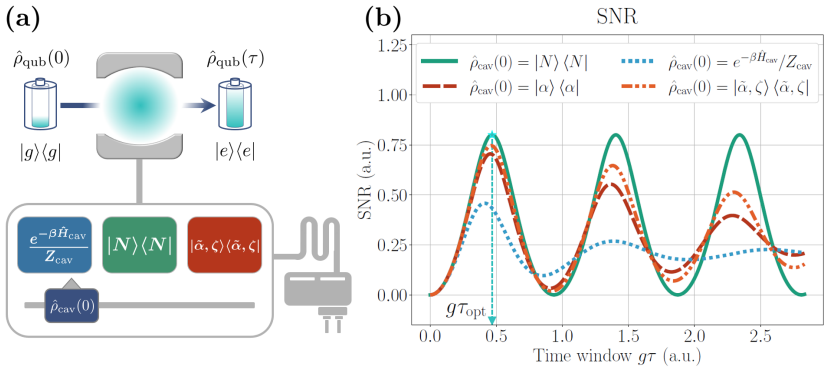

FIG. 1. (a) Scheme of the JCQB proposed in this work [4]. (b) Signal-to-noise ratio (SNR) associated with the injected energy.

Nano heat machines, efficiency and the role of inertia

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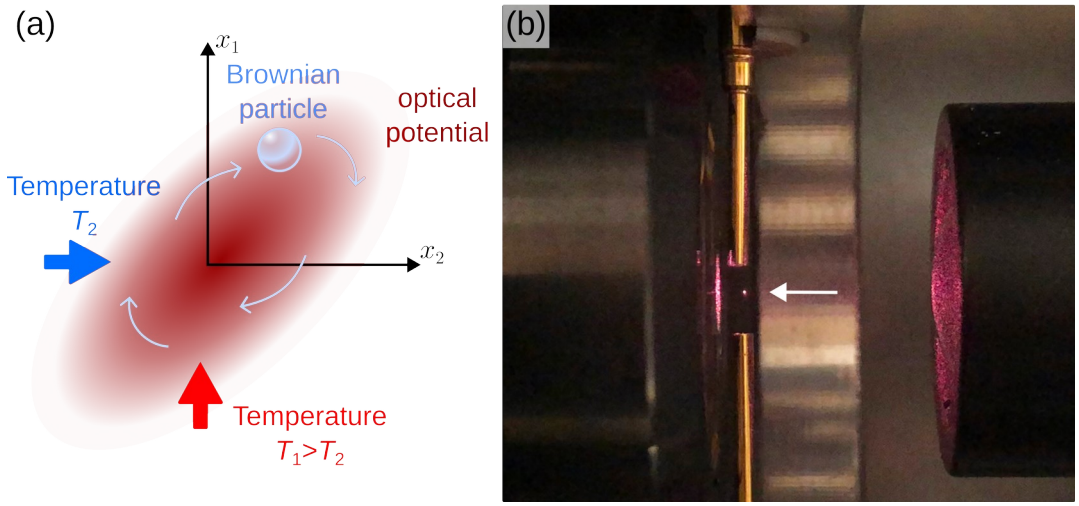
A significant question in stochastic thermodynamics is how to improve the efficiency of nanoscale systems. In this context, the role of inertia, though often neglected, is of prime importance. For example, we recently demonstrated that designing an experimentally feasible optimal protocol for compression and decompression in the inertial regime is challenging[1].



(a) Principle of Brownian Gyrator. A Brownian particle is trapped in an asymmetric potential (in red). Applying different temperatures at 45° from the potential axis provides the basis for the rotation of the particle (light blue arrows) (b) Experimental setup for the realization of the Brownian Gyrator. A 70nm radius silica nanoparticle (bright red spot) is optically trapped at the focus of the high NA objective (on the left). Two electrodes allow applying an electrostatic force to the particle to control the effective temperature of the heat baths.

The Brownian Gyrator, one of the simplest experimentally available nanoscale heat machines, offers a practical model for studying these effects. It consists of a Brownian particle trapped in an asymmetric potential coupled to two orthogonal heat baths at different temperatures. When the directions of the heat baths are not along the main axes of the potential, the particle exhibits rotational motion around the potential centers[2]. Using an optically levitated nanoparticle, we demonstrate how inertia impacts the efficiency of our Brownian gyrator.
This work paved the way for developing efficient nano-heat engines in the inertial regime.

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Entropic Cost of Statistical Inference

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Maxwell's famous gedanken experiment highlighted a profound link between information and thermodynamics. In its original form, the second law of thermodynamics, a probabilistic principle with physical implications, did not consider information, an otherwise abstract concept. In the thought experiment, an omnipotent demon is able to sort particles in a box into hot and cold groups without expending work: violating the second law of thermodynamics. This apparent violation led to a revision of the second law to incorporate information, giving physical significance to an abstract entity. In this updated framework, it was shown that the demon incurs a fundamental work cost for the complete process of gathering information and subsequently having its memory reset, reflecting the essential processes of a measurement [1].

Measurements play a significant role in science and engineering alike, serving as the foundation for constructing and testing scientific models. This significance is particularly evident in the realm of statistical inference, where the choice of measurement is often treated as a tunable parameter. In brief, the process of inferring an unknown can be divided into two distinct tasks: the physical task of measuring an observable(s), and the information-theoretic task of generating an estimate from the measurement results. In both tasks, a priori information about the unknown parameter imposes a limitation: the minimum cost for the measurement, as well as the quality of the resulting estimate. When comparing various inference strategies, the focus often rests solely on the accuracy of the estimate, neglecting the energetic costs associated with the measurements. This is a significant oversight given the real-world limitations imposed by finite resources.

In light of the above, we propose a framework that integrates the cost of measurements in the overall assessment of a statistical inference strategy. This is achieved through a metric-noise-resource style of analysis [2], wherein the metric reflects the quality of the estimate, the resource is defined as the fundamental lower bound for the expected cost of the measurements, and noise is incorporated by assuming inefficient measurements. The lower bound on the cost of using the noisy meter, and the subsequent reset, is proportional to the sum of the quantum-classical mutual information derived by Sagawa and Ueda [3] along with an additional term that accounts for the noise. The secondary term can be understood as residual mutual information between the state of the system and the inefficiencies of the meter.

We showcase our framework through practical applications in quantum information: tomography and quantum metrology. In both instances, an advantage arises by employing a more energetically efficient measure-and-reset protocol by making use of previous measurement results that leverages prior measurement results, allowing for the (expected) minimum cost of subsequent measurements to asymptotically approach zero. Our framework is especially useful for comparing multiple statistical inference strategies which make use of different measurements. Different measurement schemes are common practice in the field of multi-parameter quantum metrology, which is a future perspective for our proposed framework.

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Symmetry shapes thermodynamics of macroscopic quantum systems

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During the round table of the past QEI workshop, the question of how to efficiently compute the entropy and energy flows, and their fluctuations, in quantum systems, has been raised. This question becomes particularly difficult to answer in small and/or complex quantum systems – widely found in quantum technologies – where fluctuations cannot be neglected. The present work brings elements to answer these issues.

In our recent paper [1], we give a systematic description of how the symmetry of a quantum system determines its entropic and energetic profile, using the underlying symmetry groups. Symmetries play a fundamental role in shaping physical theories, from quantum mechanics to thermodynamics. Morevover, studying the entropic, energetic, or dynamic signatures of underlying symmetries in quantum systems is an active field of research, from fundamental questions about entropy scalings, ground state properties, and thermalization, to the optimization of quantum computing or numerical simulation procedures. Here, we show that the entropy of a system can be described in terms of group-theoretical quantities that are largely independent of the details of its density matrix. Using permutation invariance, we find that, for large N, the entropy displays a universal asymptotic behavior in terms of a function $s(\boldsymbol{x})$ that is completely independent of the microscopic details of the model, but depends only on the size of the irreducible representations of the permutation group S_N. In turn, the equilibrium state of the system and macroscopic fluctuations around it are shown to satisfy a large deviation principle with a rate function $f(\boldsymbol{x}) = e(\boldsymbol{x}) - \beta^{-1} s(\boldsymbol{x})$, where $e(\boldsymbol{x})$ only depends on the ground state energy of particular subspaces determined by group representation theory, and β is the inverse temperature. To demonstrate the power of our approach, we apply it to the – generally cumbersome – task of describing phase transitions governed by the interplay of quantum and thermal fluctuations. We focus on the transverse-field Curie-Weiss model, a minimal model of phase transition exhibiting an interplay of thermal and quantum fluctuations, and which, despite its apparent simplicity, has so far resisted analytical and numerical investigations beyond mean-field.

Our findings indicate that the group representation theory is a powerful tool for quantum thermodynamics. Using this theory should shed a new light on our understanding of entropic and energetic flows and fluctuations in complex quantum systems. Our results are also particularly relevant to characterize emergent phenomena in many-body quantum systems, where they can be used to drastically simplify problems that are otherwise difficult to tackle either analytically or numerically.

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Determining the energy consumption of a quantum algorithm running on a superconducting cat-qubit based fault tolerant quantum computer.

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Developing a quantum computer is the subject of intense academic and industrial research, due to its promise to solve classically intractable problems. As a consequence, quantum computing is developing rapidly, with recent advances suggesting the feasibility of quantum error correction on a large scale [1]. As with any nascent technology though, many questions remain, regarding the engineering feasibility of such a machine or its place in a world of finite resources for example. In both cases, a typical concern are the energy needs of a future quantum computer.

Here we focus on superconducting cat-qubits, which are presumed to use fewer physical qubits for error correction than other platforms thanks to their noise bias, a property named 'hardware-efficiency' [2,3]. As of yet, no effort has been made to quantify the energy consumption of such an approach, leaving the question of energy efficiency unanswered.

In this talk, we detail how to approach the full-stack energy consumption of a quantum algorithm running on a superconducting cat-qubit based fault tolerant quantum computer. Using the Metric – Noise – Resource methodology developed in [4] we show how individual cat-qubit gates can be optimized for their energy consumption at fixed fidelity. The assembly of these gates into a previously developed algorithm solving problems in cryptography [2], should yield a first estimate of the fundamental energy consumption of the platform. Finally, we identify the overhead cost of current enabling hardware, pointing to a future research direction for the community at large.

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Asymmetric thermalization in few-level systems

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The relaxation of an out of equilibrium open quantum system after a quench is a problem whose understanding can be as complicated as the complexity of the system and its coupling to the environment. However it is worth getting intuition about the related dynamics and being able to extract some universal features which may apply to the operation of quantum heat engines and the effect of environmental degrees of freedom in quantum information processes.

Starting from simple configurations such as a thermal qubit, a harmonic oscillator or a quantum brownian particle, and using concepts of quantum information geometry, we have identified features that reveal that the thermalization process is asymmetric depending on the initial nonequilibrium configuration **[1]**. For instance: two states (one hotter and one colder) thermalize to a thermodynamically equidistant warmer state at different speeds: the colder always thermalizes faster. Depending on the protocol, we identify different mechanisms even in the simplest cases (a qubit) which may be related either to the rate of thermal fluctuations or to notions of the third law of thermodynamics.

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Advancing quantum chemistry with quantum computing resources

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Quantum chemistry methods for electronic structure calculations aim to solve the Schrödinger equation for electronic structures where the computational cost of exact solutions increases exponentially with system size. In practice this leads to the widespread use of approximations. Some of these, such as Coupled-Cluster with a Full treatment of Singles and Doubles with perturbative Triples (CCSD(T)), are widely appreciated for their systematic nature and accuracy. However, these methods becomes computationally infeasible as system size grows, and may also be inadequate for certain types of electron interactions.

This presentation will begin by addressing the challenges posed by the need for high-accuracy methods in relevant applications. We will then explore the potential of quantum computing to achieve chemical accuracy for complex systems, with a focus on its applicability in areas like drug design. A range of strategies to incorporate quantum computing into the path toward quantum advantage will be discussed, including approaches from recent research[1, 2, 3, 4]. Finally, we will review current attempts to define and achieve quantum advantages in the field[5].

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Diamond-Based Quantum Token (DIQTOK)

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A common problem in authentication protocols is the susceptibility of key forgery by an attacker. That is, a hacker which can read the user's authentication key and impersonate them, for instance gaining illegitimate access to the user's home, their credit card, or impersonating them on the internet. However, one thing in nature cannot be cloned: quantum states. Supported by the quantum no-cloning theorem, the goal of the Diamond-Based Quantum Token (DIQTOK) is to create and develop the necessary techniques for a physical prototype of a quantum token, where the authentication key is encoded in quantum spin states of color centers in diamonds. If successful, this proof-of-principle would represent a robust technology for the highest security requirements, where any attempt of reading or cloning the quantum state would inevitably alter them. Energy consumption considerations would appear in the next phase of this project, where we concern with miniaturization and making the quantum token mobile. More specifically, how error mitigation methods for coherence extension of the quantum states can be applied with minimal energy consumption.

In this work, we present the proposed quantum token protocol, experimentally demonstrated and benchmarked on different IBM quantum hardware. We also study current techniques of nitrogen vacancy (NV) centers creation and nanopillars structuring in diamond for the fabrication of the quantum tokens. A method for ultrafast quantum state transfer between nuclear and electronic spins of the NV is proposed, based on dynamical decoupling techniques used in quantum sensing. Lastly, we present the Quantum Color Centers Analysis Toolbox (QuaCCAToo) Python package under development, containing analysis and simulation tools common for color centers, but also applicable to other quantum systems in general.

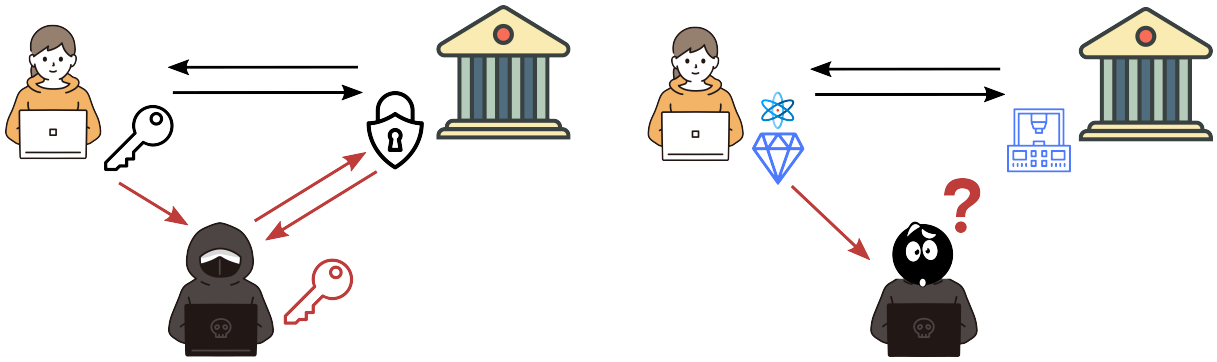

Figure: Schematic representation of a classical authentication method and the proposed quantum token protocol. Any current authentication method is susceptible to key forgery by an attacker. Whereas in a quantum token, the authentication key is stored in quantum states, which cannot by read or cloned without altering them.

Energetics of VQE algorithm
FOR THE QUANTUM ENERGY INITIATIVE 2025 WORKSHOP (QEI2025)

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Quantum computing is slated to offer a substantial advantage over classical computing, mainly for specific classes of problems informed by complexity theory. Though motivated fundamentally, the purported advantages will only be realizable in the future in the era of fault-tolerant large-scale quantum; through a developmental road-map consisting of several technological leaps in qubit quality, controllability, compilation routines, control electronics, other enabling technologies and software resulting. However, such a setup – with very demanding device parameters - appears to be at best years away, and the current hardware does not conform to such an idealized scenario, being marred with finite qubit coherence times, and imperfect operations. This type of hardware is said to belong to the noisy intermediate-scale quantum (NISQ) regime, which has a limited number of qubits (~100s), and a limited gate-set.

Various algorithms suitable for quantum computing within the limitations imposed by NISQ devices have been developed. Many NISQ algorithms are cente around the idea of a hybrid quantum-classical architecture with tunable quantum gates associated with variational parameters. Such NISQ algorithms are known to be useful for a large class of problems, including combinatorial optimization, molecular ground state energy calculation, state preparation, etc. These algorithms are broadly referred as Variational Quantum Algorithms (VQAs).

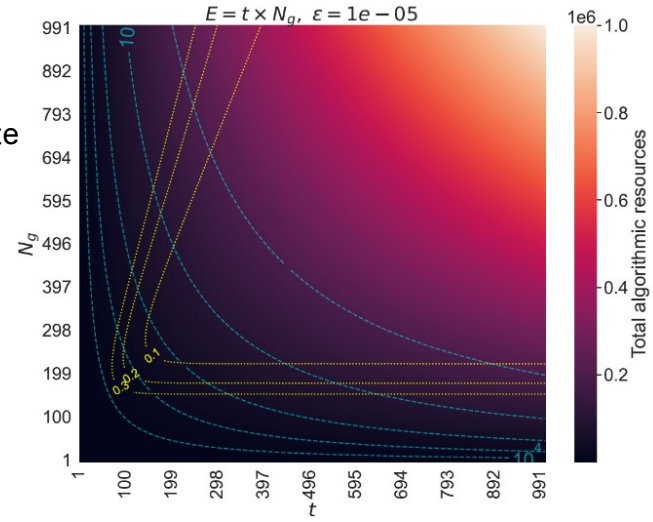

Figure 1: Isometric curves (dotted yellow lines) representing the accuracy of the results calculated by VQE superposed on the algorithmic resource consumption heatmap. The blue dotted lines represent the contours of the heatmap.

We consider energy efficiency of a VQA called the Variational Quantum Eigensolver (VQE). Such an efficiency benchmark is parametric i.e. depends on the task at hand and can be simply expressed as: efficiency = quality of the result for the task consi / energy consumption. We build a VQE algorithm for computing the ground state energy of a spin chain system (Heisenberg Model) and evaluate its energy efficiency based on the accuracy of the ground state energy and the algorithmic resource consumption in the presence of noise. Two main algorithmic resources that we identify are the number of gates in the circuit and the number of iterations of the circuit that is needed for optimization in VQE. For this energetic analysis, we adopt the Metric-Noise-Resource (MNR) framework[1] which aims to identify the minimum amount of resource (energy) that is needed to achieve a target performance metric in the presence of noise. Using this framework, we find regions of maximal energetic efficiency for the VQE algorithm on the algorithmic resource landscape (see Fig. 1). Additionally, we study various tradeoffs in the MNR sphere such as between the noise and metric, and metric and resource. Based on these tradeoffs, we also present a hardware agnostic resource optimizer.

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Impossibility of universal work extraction from coherence: reconciling axiomatic and resource-theory approaches (QEI2025)

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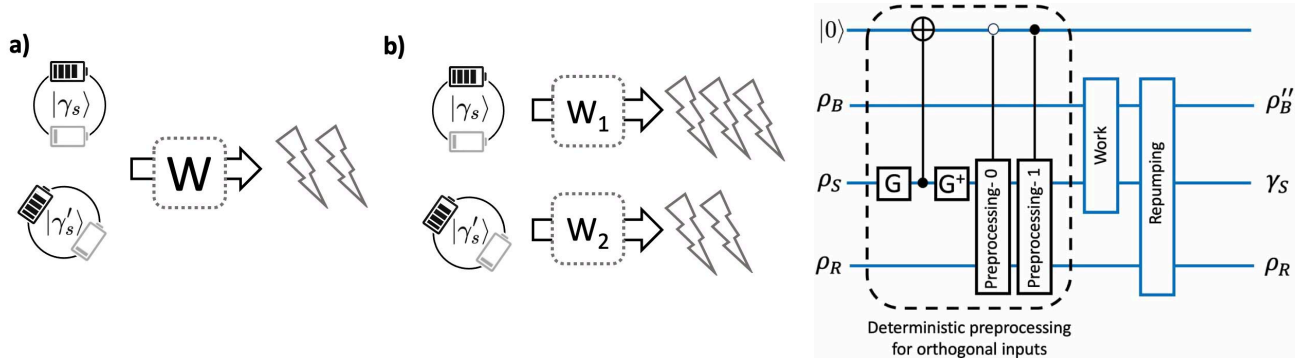
Can we get more useful work from a system that is in a superposition of energy states than a random mixture of energy states?

The usefulness of coherence for energy-related tasks is surprisingly subtle, and highly sensitive to the particular regime being considered. For example, the phenomenon of *work-locking* shows that the work extractable directly from a mixture of energy states is equivalent to that extractable from a superposition of energies. However, access to a coherent catalyst enables more work to be extracted from the superposition than the mixture. We demonstrate an important caveat to this result: any machine that can deterministically extract additional work from coherence, even with a coherent catalyst, cannot be universal. Instead, it must be a special-purpose machine for the input state from which work is being extracted.

We explain how to derive this conclusion in a very general way, using the recently proposed *constructor theory*, which aims to express laws of physics in terms of possible and impossible tasks. This has interesting implications for laws about information and thermodynamics. Our results unify the axiomatic, information-theoretic approach from constructor theory with an explicit approach from resource theories. In addition, we draw a new connection between the impossibility of a universal work extractor and the recently found *constructor-based irreversibility*, which is an exact form of irreversibility compatible with reversible (unitary) dynamics. This has been recently demonstrated theoretically and experimentally using a qubit collision-model protocol called the quantum homogenizer.

Our work has direct implications for designing unconditional, catalytic and deterministic protocols that maximize work extraction within quantum information processing technologies, and also establishes a basis from which to unify the far-reaching results from the resource-theory and constructor-theory approaches to quantum thermodynamics. These results could be extended to analyze topics such as the fundamental irreversibility of quantum computation, and the thermodynamics of multiple conserved quantities.



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Marek Winczewsk (University of Gdańsk)

Title:

Dissipation of Secrecy Resources in Quantum Networks

Abstract:

Irreversibility of quantum resources is a notorious problem: We spend more resources creating a state than we can gain. In many contexts, this gap corresponds to an energy dissipation. Estimating this gap is, therefore, important for identifying less dissipative setups in the spirit of quantum energy initiative. In future quantum networks, one of the main resources exchanged will be the quantum secure key. The problem of the irreversibility of the secure key has not been studied till recently, first observed in [arXiv:2402.17007]. We initiate the quantitative study of the irreversibility of the secure key, therefore providing lower bounds on future, inevitable (i.e., technology-independent) energy dissipation factor.

Quantum Frequential Computing: *a quadratic run time advantage for all computation*

Mischa P. Woods: *Inria, University of Grenoble Alpes. Preprint available here.*

Significance of Results

An important problem in computer science is the reduction of the runtime required to compute the solution to a computational problem.

Quantum computing attracted attention due to its ability to offer asymptotically faster solutions to select problems when compared to the best-known classical algorithm [NC10]. Moreover, this speedup is better than a constant factor—which is necessary to justify the additional engineering challenges in their construction.

It is the logical degrees of freedom which are quantum in a quantum computer. To date, it was unknown if other parts of a computer could lead to runtime speed-ups, as a function of the underlying resources, if they are quantum-mechanical rather than classical or semi-classical.

Here we prove that when the control is quantum and optimal, there is a quadratic runtime speedup as a function of the power consumed or cooling rate required, for any algorithm being implemented, when compared with optimal classical or semiclassical control. What is more, we prove that only a relatively small part of the computer architecture needs to have control which is quantum in order to achieve the advantage—drastically simplifying any such future computer. The quantum speedup originates from an increase in gate frequency.

Our approach enables a quantum runtime advantage for algorithms with no quantum-algorithmic improvement. For conventional quantum algorithms, it gives a quadratic speedup in addition to any algorithmic one.

Background and Motivation

Reducing the runtime required to solve computational problems is the end goal of many different research fields in computer science. For example, better algorithms, improved system architectures, or faster computer clock and gate speeds, can all lead to a reduction in the runtime.

Historically, all three areas of research have led to significant runtime gains. For example, algorithms for improved matrix multiplication [FBH$^+$22] have led to a speedup in a wide number of computational problems. Architectural methods such as instruction pipe-lining and out-of-order execution have also led to speedups [COLV04, Gon18]. Likewise, the clock speed of computers has increased dramatically since their inception. In 1938, the first fully mechanical analogue computer, the Z1, operated at one Hz. Later electronic computers further increased this frequency with decade-on-decade speedups until around 2003, when progress stalled in the GHz range. Since then, there has been a significant slowdown due to a breakdown in Dennard's scaling, which predicts how transistor speed increases when chips follow Moore's law [DGY$^+$74]. The breakdown was caused by changes in transistor geometry required for the continuation of Moore's-law scaling.

Similarly, improvements in classical algorithms can only take us so far. The development of quantum computing was motivated precisely because it was realized that quantum mechanics allowed for better scaling than the best-known classical algorithm in a select group of problems.

In addition to the hurdle of decreasing runtime, there is also the desire to consume less power. Computation is estimated to consume over 3% of global power generation [SN11, VHLL$^+$14] and the world's still-exploding boom in AI is predicted to drive that number up significantly—and fast [Lef23]. This work allows for faster computing without increasing power consumption, thus permitting for more power-efficient computation.

Technical Results

The paper proves 4 theorems. To start with, observe that in the context of modeling a quantum system unitarily, it follows via the quantum speed limit [Lev82, ML98, Llo00], that when the control is modeled unitarily via a time-independent Hamiltonian, the gate frequency f is lower bound by the mean initial energy E up to constants, i.e. $f \lesssim E$. Until recently, it was believed that classical systems do not satisfy any speed limit at all [SCMdC18, OO18], let alone addressing whether there is any quantum advantage. Here I derive the bound $f \lesssim \sqrt{E}$ for semi-classical states, proving that there is indeed a square-root quantum advantage.

However, these are just upper bounds for Hamiltonian dynamics which follow from taking into account that there are sequences of logical states which move the logical space within orthogonal states. Computers require more structure. Next we prove that both scalings $f \sim E$, $f \sim \sqrt{E}$ when the control is quantum and semi-classical respectively, are achievable for a Hamiltonian model consisting of a control space, logical space, and program memory, for computers capable of universal classical and quantum computing.

It's highly advantageous if not all of a computer requires a quantum-mechanical treatment, because quantum systems are far more susceptible to noise and hence error. We add additional architecture, namely an internal data bus, and prove that, while it's operating at the same data transmission speed as the gate frequency, it can operate with semi-classical states even though the gate control necessarily requires quantum states. This proves that not all components of the computer need to be quantum.

Finally, we move away from the Hamiltonian dynamics picture to a non-equilibrium steady-state dynamics, where the control is governed by a quantum self-oscillator. This is a quantum version of the classical self-oscillators which all quantum and classical computers run on [Jen13] (also see [BMD22, SWS21a, WSK$^+$19, SWS21b, CMG22, CKS$^+$23]). This self-oscillator requires power to run. We prove that the power P required to run the self-oscillator and computation (in the case of reversible gates), is proportional to the mean energy of the oscillator's state. This in turn allows us to prove that a computer, running in a non-equilibrium steady state, has an optimal gate-frequency-to-power-consumption scaling of $f \sim P$ and $f \sim \sqrt{P}$ for quantum and semi-classical control states respectively. Current quantum computers use semi-classical control only. My work proves that they could run at far higher speeds with a fraction of the power consumption if the control were also quantum. They would also generate less heat dissipation and thus require less cooling.

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Energetic Analysis of Emerging Quantum Communication Protocols

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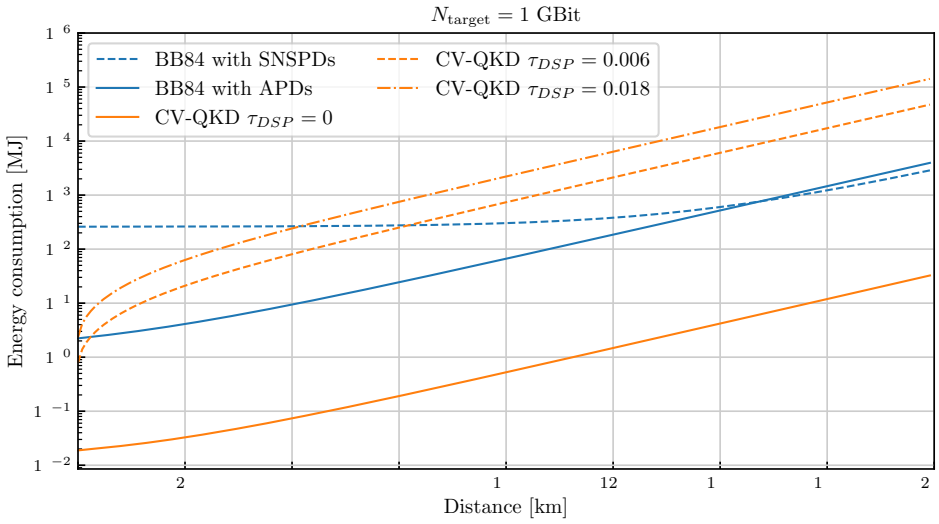
In a world with finite resources where energy demands outgrow energy generation, it is crucial to estimate how much energy quantum networks will consume prior to their deployment [1, 2, 3]. Such a study can reveal limiting factors for future implementations of networks, or even show the energetic advantages of certain quantum technologies over classical ones. This work presents the foundations of a framework to estimate the energy cost of quantum network protocols. We give a first estimation of the energy requirements of basic network functionalities, namely Quantum Key Distribution (QKD) and Conference Key Agreement (CKA), whose goals are to generate a secret private key among end users of a quantum network. The methods and hardware they use are generic to most protocols based on photonic implementations. In particular, the creation and sharing of entangled states among distant parties, believed to be the main goal of most quantum network architectures [4], are the building blocks of many other network protocols [5, 6, 7, 8, 9, 10].

To obtain concrete figures of merit, we take a hardware-dependent approach to compare different implementations of some common protocols. Namely, different QKD implementations are compared, and the implementation of networks of N nodes are analyzed, since their scaling in resources with the number of nodes is non-trivial. Using the energetic cost as a benchmark, instead of the rate or the fidelity, gives a unique perspective. For example, our simulations suggest that there exists regimes of parameters for QKD protocols where using less efficient but more energy effective detectors results in huge energy savings at the cost of increased execution time. Another example of results from this work are the discovery of distance regimes for which the usage of different wavelengths results in energy savings, and the identification of optimal protocols to achieve multipartite tasks as a function of the number of parties.



Example of result from this work : Comparison of of the energy cost to get 1Gbit of Secret key with a DV-QKD BB84 implementation with APDs detectors, SNSPDs detectors and a CV-QKD implementation with Gaussian modulation, heterodyne measurement and double polarization, including the classical costs from Digital Signal Processing (DSP).

Arxiv link: https://arxiv.org/pdf/2410.10661

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