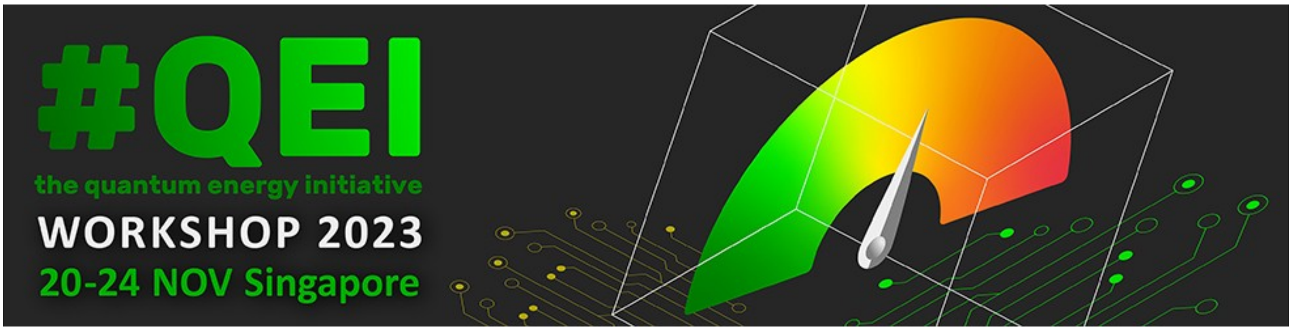

QUANTUM ENERGY INITIATIVE WORKSHOP 2023

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ABSTRACT BOOK

20-24 NOVEMBER 2023

NUSS Kent Ridge Guild House

SINGAPORE

Workshop Organizing Committee:

- Alexia Auffèves (CNRS, MajuLab, CQT)
- Yvonne Gao (NUS, MajuLab, CQT)
- Clara Fontaine (NUS, CQT)
- Olivier Ezratty (QEI)
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- Dario Poletti (SUTD, MajuLab)
- Janine Splettstoesser (Chalmers University)
- Robert Whitney (Univ. Grenoble Alpes & CNRS)

	Monday, 20th Nov	Tuesday, 21st Nov	Wednesday, 22nd Nov	Thursday, 23rd Nov	Friday, 24th Nov
0900 - 0930		Plenary talk: Zoller	Plenary talk: Ueda	Plenary talk: Matsuoka	Narasimhachar
0930 - 1000					Anders
1000 - 1030		Huard	Walschaers	Ng	Soret (20 min)
1030 - 1100	Presentation of QEI	Tea Break	Tea Break	Tea Break	Tea break
1100 - 1130		Plenary talk: Paik	Contributed talks: 1. Ali 2. Buffoni 3. Strauss	Fitzsimons	Cortinas
1130 - 1200	Plenary talk: Kosloff			Contributed talks: 1. Henaff 2. Seskir 3. Fellous-Asiani (3 x 20min)	Lutz
1200 - 1230		Brennen	Lunch		Closing
1230 - 1300	Lunch	Lunch		Lunch	Lunch
1300 - 1330			Gu		
1330 - 1400			Contributed talks: 1. Estarellas 2. Yehia (2 x 20min)	Contributed talks: 1. Meng 2. Monsel 3. Nazir (3 x 20min)	
1400 - 1430	Watanabe	Contributed talk: Goetz (20 min)			End
1430 - 1500	Kwek			Round Table	
1500 - 1530	Tea Break	Poster Session + Drinks	Free		
1530 - 1600	**Industry Panel :** Bertin (EDF), Paik (IBM), Pang Ki Khoon, (AWS), Dunlin (Thales) Moderator: Jaiswal (Singapore National Quantum Office)				
1600 - 1630					
1630 - 1700					
Evening	Invited Speakers Dinner *(by invitation)*		Colloquium and Cocktail at the French Embassy *(by invitation)*	**18h30** Conference Dinner for **all** participants **same room as workshop**	

Recovery of qubit state after noisy leakage in high-dimensional space

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Experiments often encode qubit states in physical systems that have many more physical dimensions. Unfortunately, environmental noise can cause the logical qubit to leak into these dimensions, compromising the qubit nature of the state. This causes unwanted artefacts, such as increased entropies. I will describe a new method to recover a meaningful qubit state from a known noisy high-dimensional state [1]. This method is valid for many physical situations where noise acts separately on two subspaces. As an example, we apply the method to the tomographically obtained states of a microwave cavity, which was used in a Maxwell demon experiment [2]. We find excellent recovery of the encoded state and a massive reduction in entropy. The new recovery method paves the way for quantum experiments and technologies to extract meaningful qubit information from a jungle of noise.

[1] J. Anders, S. Sevitz, et al, in preparation.
[2] N. Cottet, et al., “Observing a quantum Maxwell demon at work”, PNAS 114, 7561 (2017).

Invited Talk

Distributed Consensus by Quantum Sampling

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Reaching consensus in an adversarial network without a centralized authority has broad applications in commerce and communications. The best-proven method is proof-of-work (PoW) which requires nodes, aka miners, to compete to verify proposed transactions by proving a certain amount of computational effort has been expended solving a one-way function. Current PoW protocols have two deficiencies, they are not quantum future-proofed, and they incentivize the adoption of fast special-purpose devices with escalating energy costs as network demand increases. For example, in 2022 the Bitcoin network consumed more electrical energy than the country of Sweden. We propose an alternative PoW protocol using coarse-grained quantum boson sampling that exploits the classical hardness of approximating the output distribution of photons propagating in a multimode interferometer. The protocol requires miners to perform full boson sampling by generating samples using input states dependent on the current block information. These samples are then post-processed using a binning strategy known only after the samples are committed to the network and allows for efficient validation and rewarding. By combining rewards to miners committing honest samples together with penalties to miners committing dishonest samples, a Nash equilibrium is found that incentivizes honest players. The scheme works for both Fock state and Gaussian boson sampling and provides dramatic speedup and energy savings relative to computation by classical hardware.

Quantum effects in the thermalization of a double-well

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Yale University

To autonomously stabilize a Schrödinger cat-qubit, we have engineered a microwave quantum circuit with two competing Hamiltonian terms [1]. A Kerr nonlinearity produces an energy proportional to the number of photon pairs, and a squeezing drive coherently breeds or annihilates photons in pairs. In phase space, the Hamiltonian resulting from the addition of these two terms presents a double-well structure, at the bottom of which a Schrödinger cat-qubit is stabilized. The bit-flip errors in this encoding are caused by thermal activation across the wells [2]. The experimental optimization of this qubit led us to a few surprises and a deeper understanding of thermalization in this double-well. I will show you how Arrhenius' law is generally modified in the highly quantum regime where we operate and how we use a rare form of quantum interference in the classically forbidden region to improve our qubit performance [3, 4].

References:

[1] https://www.nature.com/articles/s41534-023-00745-1

[2] https://arxiv.org/abs/2209.03934

[3] https://arxiv.org/abs/2211.04605

[4] https://journals.aps.org/pra/abstract/10.1103/PhysRevA.107.042407

Title to be announced

Joe Fitzsimons

joe@horizonquantum.com

Horizon Quantum Computing, Singapore

Invited Talk

Title to be announced

Mile Gu

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Centre for Quantum Technologies, National University of Singapore

Invited Talk

Energetics of a resonantly driven transmon qubit: measurement backaction and information fueled engine

Benjamin Huard

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Ecole Normale Supérieure de Lyon, France

Qubits are physical, a quantum gate thus not only acts on the information carried by the qubit but also on its energy. What is then the corresponding flow of energy between the qubit and the controller that implements the gate? In this talk, we exploit a superconducting platform to answer this question in the case of a quantum gate realized by a resonant drive field. During the gate, the superconducting qubit becomes entangled with the microwave drive pulse so that there is a quantum superposition between energy flows. We measure the energy change in the drive field conditioned on the outcome of a projective qubit measurement. We demonstrate that the drive's energy change associated with the measurement backaction can exceed by far the energy that can be extracted by the qubit. This can be understood by considering the qubit as a weak measurement apparatus of the driving field. We then discuss an experiment that realizes an engine able to extract work from the measurement backaction of a qubit. The extracted work is directly measured in the reflection of a resonant field that drives the qubit.

Where are we with the construction of a quantum computer?

Benjamin Huard

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Ecole Normale Supérieure de Lyon, France and Alice&Bob, Paris, France

Triggered by the amazing predicted computing power of quantum processors, many academic groups and companies are hard at work to build such a machine. We will discuss which quantum properties are at play in this yet untapped computing power. We will also see why quantum properties are fragile and require taming their natural enemy: quantum decoherence. We will then explain where we stand and what are the main challenges ahead on the path towards the realization of a quantum computer.

Plenary Talk

Quantum Thermodynamics, Quantum control and their resources

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Control of quantum systems is essential for the realization of contemporary quantum technology. Quantum control theory addresses the following issues:

- Controllability: Can we reach the objective with the available controls?
- Resources: what are the resources required for obtaining the objective?
- Constructive control mechanisms.
- Optimal control theory.

In reality, any quantum system is open. External intervention transforms the unitary dynamics of a closed system into a non-unitary evolution of an open one. We can classify three significant sources of such intervention: I. A thermal environment. II. Back-action due to quantum measurement. III. Noise originating from the external controller. Optimal control theory formulates the dynamical equation of motion as a constraint. Additional constraints are demand on the resources. Thermodynamics was developed to put limits on converging of resources. In addition, the quantum dynamical equations have to be a thermodynamically consistent to be correct. This in turn imposes a link between the control agents and the dynamical equation, leading to control-dependent dissipation. This relation serves as the key element for open system control. The control paradigm is displayed by analyzing entropy changing state-to-state transformations, such as heating and cooling. The difficult task of controlling quantum gates is achieved for non-unitary reset maps with complete memory loss. In addition, we identify a novel mechanism for controlling unitary gates by actively removing entropy from the system to the environment.

S. Kallush, R. Dann, and R. Kosloff. ”Controlling the uncontrollable: Quantum control of open-system dynamics.” Science Advances 8, (2022): eadd0828.

Aviv Aroch, Ronnie Kosloff, Shimshon Kallush, ”Mitigating controller noise in quantum gates using optimal control theory.” arXiv:2309.07659 (2023).

Invited Talk

Ecofriendly Chip-Based Quantum and Classical Neural Networks

Kwek Leong Chuan[1,2,3]
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1 Centre for Quantum Technologies, National University of Singapore 117543, Singapore
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3 National Institute of Education & Inst. of Advanced Studies, Nanyang Technological University 637616, Singapore

Integrated silicon based photonic circuits do not dissipate as much energy as electronic circuit once it is properly trained and fabricated. There are therefore some advantages towards the fabrication of such chips. We briefly discuss our recent efforts towards ecofriendly integrated silicon based photonic chips for quantum and classical neural networks.

References

please refer to webpage: dr.ntu.edu.sg/cris/rp/rp01416/selectedPublications.html

Invited Talk

Quantum statistics as an energy source

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Heat engines convert thermal energy into mechanical work both in the classical and quantum regimes. However, quantum theory offers genuine non-classical forms of energy, different from heat, which so far have not been exploited in cyclic engines. I will present an experimental realization a quantum many-body engine fuelled by the energy difference between fermionic and bosonic ensembles of ultracold particles that follows from the Pauli exclusion principle. Employing a harmonically trapped superfluid gas of Li atoms close to a magnetic Feshbach resonance allows one of effectively change the quantum statistics from Bose–Einstein to Fermi–Dirac, by tuning the gas between a Bose–Einstein condensate of bosonic molecules and a unitary Fermi gas (and back) through a magnetic field. The quantum nature of such a Pauli engine is revealed by contrasting it with an engine in the classical thermal regime and with a purely interaction-driven device. These results establish quantum statistics as a useful thermodynamic resource for work production.

Plenary Talk

Title to be announced

Satoshi Matsuoka

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Invited Talk

Energy costs of quantum technologies

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Yale-NUS College and the Centre for Quantum Technologies, National University of Singapore

Quantum computation with near-future devices will remain limited by the noise in the physical components. The only way forward, to get to large-scale and useful quantum computers, is through active error correction and associated fault-tolerant schemes. I will discuss some aspects of this, focusing in particular on the resource costs of doing fault-tolerant quantum computing, and describe a framework for minimising energy requirements for a computational task. I will also touch on recent work looking at the energy costs of quantum metrology.

Invited Talk

Formalization of measurement-based uncomputation, with applications to quantum arithmetic and cryptographic attacks.

Adithya Sireesh, Varun Narasimhachar[1]†, Alessandro Luongo[2]

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2. Centre for Quantum Technologies, National University of Singapore, Singapore.

In this talk we report recent results on quantum circuit optimization. We start by introducing a technique called measurement-based uncomputation. We then present two applications. First, we propose new circuits for arithmetic subroutines that are ubiquitous in quantum algorithms. Our new circuits enable improvements over the state-of-the-art in attacks on elliptic curve cryptography. Secondly, we improve over the current state-of-the-art implementation of Shor's algorithm for integer factorization.

How can we help sustainability and global energy efficiency with quantum computing?

Hanhee Paik

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IBM Quantum, IBM T. J. Watson Research Center

Quantum computing has a lot of potential to help global efforts of environmentally-friendly energy consumption and sustainability. Quantum computing scientists and subject matter experts are already looking into applications of quantum computing to solve sustainability problems which are challenging and nearly intractable with classical computing without using a lot of computing resources and energy. I would like to share the current IBM's effort towards energy-efficiency and sustainability. As a quantum community, we should continue our research and development of new quantum algorithms and applications that are more compute-resource efficient to be an alternative or can be integrated with existing classical computing algorithms. Regarding developing quantum hardware, we need to put our effort to design energy efficient quantum computing platforms.

Maxwell’s demon, Gibbs paradox, and thermodynamic energy cost of information processing

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The second law of thermodynamics presupposes a clear-cut distinction between the controllable and uncontrollable degrees of freedom by means of macroscopic operations. The cutting-edge technologies in quantum information and nano-science seem to force us to abandon such macroscopic notion in favor of the distinction between the accessible and inaccessible degrees of freedom. I will discuss how this paradigm shift can be achieved through integration of the second law of thermodynamics with feedback control to create a new research field of information thermodynamics [1]. I will discuss the minimum energy cost required for measurement and erasure of information [2]. The total energy cost of measurement and information erasure resolves the paradox of Maxwell’s demon [3], as confirmed experimentally [4]. Information thermodynamics thus formulated unifies the modern fluctuation theorem with information theory, leading to an unexpected consequence that the inclusion of the factor 1/N! in the thermodynamic entropy introduced by Gibbs (the Gibbs paradox) is equivalent to the validity of the fluctuation theorem with absolute irreversibility for gas mixing [5]. Finally, I will discuss how Maxwell’s demon can be utilized for quantum transport [6].

References

[1] T. Sagawa and M. Ueda, Phys. Rev. Lett. 100, 080403 (2008).
[2] T. Sagawa and M. Ueda, Phys. Rev. Lett. 102, 250602 (2009).
[3] T. Sagawa and M. Ueda, Phys. Rev. Lett. 104, 090602 (2010).
[4] S. Toyabe, T. Sagawa, M. Ueda, E. Muneyuki, and M. Sano, to appear in Nat. Phys. 6, 988 (2010).
[5] Y. Murashita and M. Ueda, Phys. Rev. Lett. 118, 060601 (2017).
[6] K. Liu, M. Nakagawa, and M. Ueda, arXiv: 2303.08326.

Resource for a quantum computational advantage in photonic quantum computing

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Quantum technologies promise dramatic improvements over classical devices. For a range of applications, optics is a promising platform to implements such quantum technologies. We have a long history of manipulating light, and it is reasonably robust to detrimental decoherence effects. This allows, for example, the creation of entangled states with thousands or even millions of modes. However, our enthusiasm must be tempered, since quantum technologies often require highly non-Gaussian states of light to unlock their full potential.

In this talk, we will first focus on computational aspects and show that every bosonic quantum computation can be recast into a continuous-variable sampling protocol where all computational resources are contained in the input state [1]. Using this reduction, we derive a general classical algorithm for the strong simulation of bosonic computations, whose complexity scales with the non-Gaussian stellar rank of both the input state and the measurement setup. We further study the conditions for an efficient classical simulation of the associated continuous-variable sampling computations and identify an operational notion of non-Gaussian entanglement based on the lack of passive separability as a requirement. In the second part of the talk, we will introduce new techniques, based on artificial neural networks, to detect such non-Gaussian entanglement.

References

[1] U. Chabaud and MW, Resources for Bosonic Quantum Computational Advantage, Phys. Rev. Lett. 130, 090602 (2023)

Quantum performance of microscopic thermal machines under outcoupling

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Advances in technology so far have enabled us to fabricate the thermal machines at the submicron to nanoscale. Especially in the last decade, great attention has been paid to so-called quantum heat engines (QHEs), microscopic heat engines whose working substance is a quantum system.

While the performance of QHEs are commonly accessed for a single isolated engine for a single cycle, their actual performance when they are coupled to an external system to extract work is a non-trivial and important issue since QHEs are susceptible to the outcoupling due to their smallness. For the last few years, we are interested in quantum effects emerging in the performance of outcoupled QHEs [1, 2]. What we have found is that, when multiple indistinguishable bosonic QHEs are coupled to an external system, the internal energy change of the external system exhibits an enhancement arising from permutation symmetry in the ensemble, which is absent when the latter consists of distinguishable engines [2]. We have also found that, when a QHE undergoes an operation over multiple cycles, the total energy change in the external system performed by the engine need not be proportional to the number of cycles [1].

This talk gives an overview of the above works on outcoupled QHEs. Our recent result about positive effects of decoherence on the charging of quantum batteries is also presented.

References:

1. G. Watanabe, B. P. Venkatesh, P. Talkner, and A. del Campo, Quantum Performance of Thermal Machines over Many Cycles, Phys. Rev. Lett. **118**, 050601 (2017).
2. G. Watanabe, B. P. Venkatesh, P. Talkner, M.-J. Hwang, and A. del Campo, Quantum Statistical Enhancement of the Collective Performance of Multiple Bosonic Engines, Phys. Rev. Lett. **124**, 210603 (2020).

Exploring Large-Scale Entanglement in Quantum Simulation

Peter Zoller

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We report experimental investigations of entanglement based on the entanglement Hamiltonian, as an effective description of the reduced density operator for large subsystems. We prepare ground and excited states of a 1D XXZ Heisenberg chain on a 51-ion programmable quantum simulator and perform sample-efficient “learning” of the entanglement Hamiltonian for subsystems of up to 20 lattice sites. Our experiments provide compelling evidence for a local structure of the entanglement Hamiltonian. This observation marks the first instance of confirming the fundamental predictions of quantum field theory by Bisognano and Wichmann, adapted to lattice models that represent correlated quantum matter. Our results also show the transition from area to volume-law scaling of Von Neumann entanglement entropies from ground to excited states. We anticipate that our findings and methods have wide-ranging applicability to revealing and understanding entanglement in many-body problems with local interactions including higher spatial dimensions.

* In collaboration with Manoj K. Joshi, Christian Kokail, Rick van Bijnen, Florian Kranzl, Torsten V. Zache, Rainer Blatt, Christian F. Roos, based on arXiv:2306.00057

TALK

Thermally driven quantum refrigerator autonomously resets superconducting qubit

Mohammed Ali Aamir[1*], Paul Jamet Suria[1] José Antonio Marín Guzmán[2], Claudia Castillo-Moreno[1], Jeffrey M. Epstein[2,3], Nicole Yunger Halpern[2,3]†, and Simone Gasparinetti[1‡]

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While refrigerators form a critical technology, quantum refrigerators remain in their infancy. This is evidenced by the scarcity of quantum-refrigerator experiments and particularly the lack of experiments demonstrating *useful* quantum refrigerators. To be practical in real-world applications, a quantum refrigerator must accomplish more than it costs to control and to cool down (so that the refrigerator exhibits quantum behaviors), must scale to impactful sizes, and should leverage naturally available heat baths.

We present a quantum refrigerator made of superconducting qudits (*d*-level quantum systems) connected to heat baths realized with the thermal radiation fields in waveguides. We use it to autonomously reset a transmon qubit to a temperature below every available bath's temperature. The refrigerator is fueled by an engineered three-body interaction between the target qubit and two auxiliary qudits coupled to thermal environments. The environments consist of microwave waveguides populated with synthesized thermal photons. The target, if initially fully excited, reaches a steady-state excited-level population of $5 \times 10^{-4} \pm 5 \times 10^{-4}$ (an effective temperature of 23.5 mK) in about 1.6 μs, in agreement with theoretical simulations. Our proof-of-concept refrigerator shows that quantum thermal machines can be integrated with quantum processing units to perform useful tasks. Our refrigerator also initiates a path to experimental studies of quantum thermodynamics using superconducting quantum circuits coupled to propagating thermal microwave fields.

TALK

Cooperative quantum information erasure

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We will present a new method for quantum information erasure that exhibits exceptional performance. The protocol is able to collective erase N qubits at once at nearly Landauer energy cost, a short time duration on the order of microseconds, and an impressively high success rate. This is made possible by exploiting cooperative effects associated with spontaneous symmetry breaking (SSB) and quantum tunnelling phenomena, which represent a shift from traditional algorithmic cooling methods.

We will also present some new results regarding the strengths of the interactions needed to make this cooperative effect significant and scaling results for various system parameters. As an example, the method is expected to perform better as N increases due to the emergent phenomenon occurring in the large N limit. This is in contrast to the expectation in quantum information theory that larger systems and/or larger rates of erasure success require increasingly complex or longer protocols. Moreover, the present method crucially relies on the fact that the qubit network is an open quantum system. Environmental noise is paradoxically found to be key for qubit purification.

The work highlights the significance of NISQs (noisy intermediate-scale quantum devices) for discovering new physics in the quantum regime. The noisy nature of the annealer employed in the experiments was crucial for discovering the phenomenon of cooperative quantum information erasure. The very possibility of accessing the device remotely and experimenting with it made the discovery quick and not expensive.

Finally, the method can be readily employed to initialize many qubits effectively in a quantum state of high purity and long duration on next-generation quantum computers, which is an essential feature for the long term development of these devices.

References:

1. Buffoni, L., & Campisi, M. (2023). Cooperative quantum information erasure. *Quantum*, *7*, 961.
2. Buffoni, L., & Campisi, M. (2023). In preparation.

TALK

Evaluating the energy efficiency of HPC vs Superconducting based Quantum Computers

Jordi Riu[1], Jofre Valles[2], **Marta P Estarellas**[1]†, Albert Solana[1] and Artur García-Sáez[2]

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Most quantum computing use-cases are currently being tackled using High Performance Computational (HPC) means. However, present HPC centers are reaching their limits in computing capacity incurring huge overheads both in terms of price and energy demands. The advantage of quantum computation is often looked at from the prism of computational runtimes. Nevertheless, the concept of quantum advantage has other dimensions that go beyond this criterion. One of them is precisely energy consumption. In this talk we will present our recent developments in benchmarking energy demands of both HPC machines and superconducting based quantum computers for a given set of tasks, considering how this scales with the size of the problem at hand. Part of these results have been developed in the context of Qilimanjaro Quantum Tech and BSC's contribution in the Spanish CUCO project (cuco.tech/en), which has as a goal to evaluate the capabilities of quantum computing in strategic industries, including its application in the path to a more sustainable way of doing heavy computations.

TALK

Minimizing the power and energy consumption of scalable full-stack quantum computers

Marco Fellous-Asiani,[1,2,*] Jing Hao Chai,[2,3] Yvain Thonnart,[4]
Hui Khoon Ng,[5,3,6] Robert S. Whitney,[7] and Alexia Auffèves[2,6]
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In the race to build scalable quantum computers, minimizing their resource consumption becomes crucial. It mandates a synergy of fundamental physics and engineering : the former for the microscopic aspects of computing performance, and the latter for the macroscopic resource consumption. With this aim in mind, we propose a methodology dubbed Metric-Noise-Resource (MNR) able to quantify and optimize all aspects of a full-stack quantum computer, bringing together concepts from quantum physics (e.g., noise on the qubits), quantum information (e.g., computing architecture and type of error correction), and enabling technologies (e.g., cryogenics, control electronics, and wiring) [1]. This holistic approach allows us minimize the resource cost of the computer. As a proof of concept, we use MNR to minimize the power consumption of a full-stack quantum computer, performing fault-tolerant computing with a tar- get performance for the task of interest [1]. Comparing this with a classical processor performing the same task, we identify a quantum energy advantage in regimes of parameters distinct from the commonly considered quantum com- putational advantage. This provides a previously overlooked practical argument for building quantum computers. While our illustration uses highly idealized parameters inspired by superconducting qubits with concatenated error correction, our methodology is universal – it applies to other qubits and error-correcting codes – and provides experimenters with guidelines to build energy-efficient quantum processors. In some regimes of high energy consumption, it can reduce this consumption by orders of magnitudes. Overall, our methodology lays the theoretical foundation for resource-efficient quantum technologies.

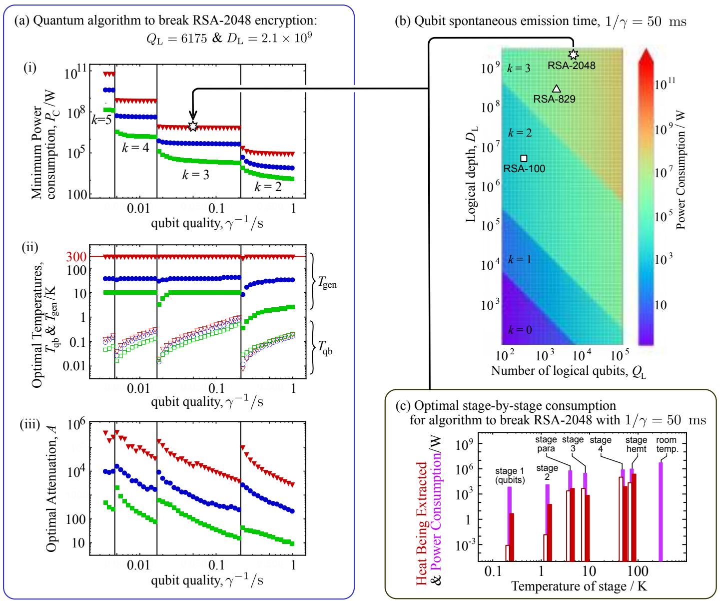

Figure 1. (a.i) : Minimum power consumption as a function of the qubit lifetime at $0K$ allowing to successfully crack RSA-2048. The colors represent different values of heat dissipated by the classical electronics (from idealized Cryo-CMOS in red to SFQ in green). (a.i) to (a.ii) Optimal computing architecture (temperatures, attenuation, number of physical qubits per logical qubits) allowing to reach this minimum. (b) Minimum power consumption, as a function of the quantum algorithm implemented, for CMOS-based electronics, with a qubit lifetime at $0K$ being $1/\gamma = 50\,ms$. The "star point" is Shor's algorithm cracking RSA-2048. (c) Heat extracted in the cryogenic system per cryogenic temperature stage, for this same point.

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[*] fellous.asiani.marco@gmail.com

[1] Marco Fellous-Asiani, J. H. Chai, Y. Thonnart, H. K. Ng, R. S. Whitney, and A. Auffèves, Optimizing resource efficiencies for scalable full-stack quantum computers, arXiv 10.48550/arXiv.2209.05469 (2022), 2209.05469.

TALK

ENERGY-SAVING RISE OF QUBIT COHERENCES

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Quantum coherence is a quantity that captures the degree to which a quantum state contains a superposition on a selected basis. It is known to be an essential resource for upcoming quantum technologies but also relevant for quantum thermodynamics and quantum gravity.

Thus, gaining insight into generating such superpositions is essential for the efficient functioning of such technologies and a more fundamental understanding of quantum theory. Understanding minimal requirements for its appearance is a fundamental problem in quantum theory.

Until now, it has risen from an external strong coherent pump operating quantum bits in a semiclassical regime. This pump is a vast coherent energy external overhead. It will be a significant saving if quantum coherence can rise from small incoherent energy.

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 linearization 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 superconducting qubits, trapped ions 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 [1-7].

By showing that nonlinear systems can substitute for intense external driving, we also indicate the potential of this methodology for the emerging concern with quantum energetics.

Topic: (1) Fundamental quantum devices

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TALK

Power per Qubit Meets the Rebound Effect

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Earlier this year at the World Economic Forum 2023, a discussion of the quantum computer's role as an emerging technology was highlighted[1], with comparisons to AI, along with quantum computers' mutual support of supercomputers. A distinguished audience member asked if quantum computers can help improve the efficiency of supercomputers' energy use, due to what he claimed accounted for 20% of electricity use in California.

Indeed, according to Manner, 2022[2], the performance and energy efficiency of ICT hardware have increased by up to a million-fold in the past 30 years, but energy consumption of the sector is also growing. Thus, there is an adverse development termed the *rebound effect*, where most industry sectors can lower their carbon footprint, while the ICT sector increases its consumption.

Anderson et al, 2022[3] and Manner, 2022 argue that the carbon-intensity of datacenter computing can be addressed with *software-centric* approaches, while we suggest a *hardware-perspective* to the rebound effect by *solving many more problems* as one becomes more energy efficient. In quantum computing, this view leads to a ***benchmarking*** concept such as ***power per qubit***[4]*(W/QB).* Here we provide estimates of IQM's energy consumption and its future optimisation, to further develop this concept.

Currently, IQM's product lines are converging to an energy consumption per qubit of < **380 W / QB**,

- 5 QB → 15 kW
- 20 QB → 32 kW
- 54 QB → 34 kW
- 128 QB → 49 kW

due to:

- Electronics ≈ 130 W / QB
- Cryostat vacuum and pumping system ≈ 23 W / QB
- Cryocooler / compressor ≈ 230 W / QB

Total ≈ 380 W / QB

Future Optimisation for 500 QB of IQM's product lines indicate an energy consumption per qubit of ≈ **100 W / QB**, by applying:

- Higher electronics integration ≈ 20 W / QB
- Higher cryocooler / compressor efficiency ≈ 6 W / QB
- Improved cryogenic hardware and cabling density ≈ 78 W / QB

Total ≈ 100 W / QB

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TALK

Pulsed approach to reservoir computing towards quantum protocols

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Our work aims at the implementation of quantum enhanced machine learning protocols in a Continuous Variables photonics platform. It focuses on the implementation of protocols based on network structures, like quantum reservoir computing, via multimode quantum optics. Classical reservoir computing is a framework for computation derived from recurrent neural network theory. It is particularly adapted in efficiently handling temporal dynamical tasks, it is already at the state-of-the-art in vision and speech recognition, and it is currently actively investigated for systems control like adapting filtering and noise reduction or prediction. Photonics offers timely settings for fast, scalable and energy efficient time series processing and has already enabled great advances in classical RC. CV photonics system are not only the natural setting for extending the reservoir computing in the quantum domain, but also, they are advantageous in term of energy consumption, because they operate at room temperature (without the need of cryogenic temperatures or superconducting devices).

We recently implemented a classical optical reservoir computing protocol using a pulsed laser [Fig. 1]. Laser pulses are used as nodes of the reservoir and the information is encoded in the phase of these pulses via electro-optical modulations [1].

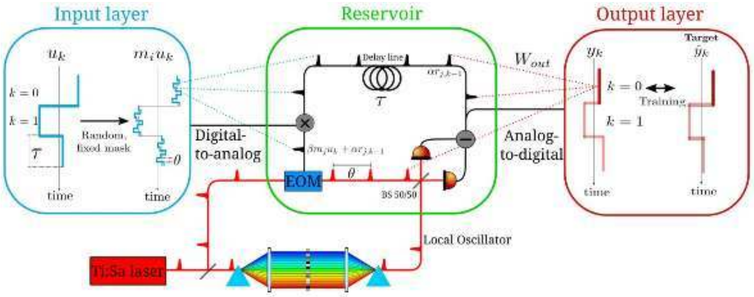

Fig. 1: Experimental setup of the optical reservoir computing protocol.

Moreover, we have generated multimode squeezed vacuum states via PPKTP waveguides pumped via optical field derived from the same pulsed laser source. Such non-linear process generates several squeezed spectral modes associated to each pulse of the laser source and so at the full repetition rate of 156MHz [2].The goal is the merging of the two experiments in order to implement a quantum reservoir computing protocol. It has been in fact recently shown [3,4] that the use of squeezed light may increase the processing capacity of the reservoir computing protocol.

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The nonequilibrium cost of accurate information processing

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At the fundamental level, information is stored into patterns that stand out from the thermal fluctuations of the surrounding environment. In order to achieve accurate information processing, deviations from thermal equilibrium should be generated. This means that any information processing machine needs an initial supply of systems in a non-thermal state, which either encodes information or enpowers the process. For a general information processing task, a fundamental question is: what is the minimum amount of nonequilibrium needed to achieve a target level of accuracy? This question is especially prominent at the quantum scale, where many tasks cannot be achieved perfectly even in principle, as illustrated by the no-cloning theorem.

Using resource theory framework, we established a fundamental tradeoff between accuracy and nonequilibrium, valid at the quantum scale and applicable to arbitrary information processing tasks. This can be regarded as complementary results relative to the stochastic thermodynamics approach. Our main result is a limit on the non-equilibrium cost c to achive accuracy F, expressed in terms of an entropic quantity κ, which we call the reverse entropy, associated to a time reversal of the information processing task $\mathcal{T}$,

$$c_{\mathcal{T}}(F) \geq \kappa_{\mathcal{T}} + \log F\,, \tag{1}$$

The limit is attainable in a broad class of tasks, including all deterministic classical computations and all quantum extensions thereof. For the task of erasing quantum information, our limit provides, as a byproduct, the ultimate accuracy achievable with a given amount of work. For the tasks of storage, transmission, and cloning of quantum information, our results reveal a thermodynamic advantage of quantum setups over all classical setups that measure the input and generate their output based only on the measurement outcomes. In the cases of storage and transmission, we show that quantum machines can break the ultimate classical limit on the amount of work required to achieve a desired level of accuracy. This result enables the demonstration of work-efficient quantum memories and quantum communication systems outperforming all possible classical setups, and it gives a thermodynamic way to witness quantumness.

Our results, recently published in Nature Communication [1], establish a direct link between thermodynamic resources and the accuracy of information processing. They set an ideal target for the design of new devices, and provide a framework for demonstrating a thermodynamic advantage of quantum devices in fundamental tasks such as storing, copying, and transmitting information.

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TALK

ROLE OF NONEQUILIBRIUM FLUCTUATIONS AND FEEDBACK IN A QUANTUM DOT THERMAL MACHINE

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We are interested in producing work by exploiting different resources. One possibility is to use information acquired on a system (the working substance) to apply ***feedback***, implementing a Maxwell's demon based engine. Another possibility is to harness ***nonthermal fluctuations*** to produce work ***in the absence of any average particle or energy flow*** between the resource and working substance. This would allow for the recycling of waste heat from other processes, which typically does not have a thermal distribution. Here, we study a thermoelectric engine combining both possibilities to generate work in the form of a steady-state current against a potential bias. We investigate the respective roles of information and nonthermal fluctuations in the performance of this engine.

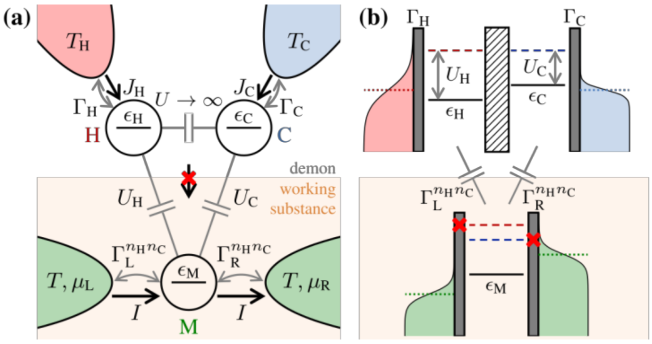

Figure 1: (a) Setup under study: three capacitively coupled quantum dots coupled to electronic reservoirs at different temperatures and chemical potentials. The lower half (orange) is the working substance while the upper half (white) corresponds to the demon. (b) Energy picture of the dots and the reservoirs they are coupled to. The tunnel couplings of the dot M depend on the occupations n_H and n_C of the demon dots H and C.

Specifically, we study a three-quantum-dot setup in which one dot is coupled to two electronic reservoirs at different chemical potentials (the working substance) while the other two dots are respectively in contact with a hot and a cold reservoir (the demon), see Fig. 1. Here, the nonthermal resource allowing for work production [1] is created by mixing two thermal distributions. Furthermore, the capacitive coupling between the dots creates an autonomous feedback mechanism that can participate in work extraction and can be interpreted as an autonomous Maxwell's demon scheme [2]. We analyze the current fluctuations with full-counting statistics and information flows with a stochastic trajectory approach. Based on this, we optimize the engine operation by favoring certain trajectories, e.g., the ones that produce the most work or that come with the lowest output fluctuations [3].

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Quantum work statistics at strong reservoir coupling

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Characterising the energetic exchanges between quantum systems, their external control fields, and their surrounding heat reservoirs lies at the heart of quantum thermodynamics. In particular, as these exchanges are fundamentally stochastic at the quantum level, it becomes crucial to determine not just their average behaviour, but also the statistics of their underlying probability distributions. For example, one may want to minimise fluctuations in useful energy (work) to enhance the consistency of thermodynamic protocols, but this may in turn have an unwanted bearing on other thermodynamic properties of the system. Moreover, for mesoscopic and quantum mechanical systems, the usual macroscopic approximation of ignoring system-reservoir correlations and coupling energies becomes suspect. This motivates the study of quantum work statistics beyond weak-coupling regimes.

However, determining the stochastic work done on a quantum system while strongly coupled to a reservoir is a formidable task, requiring the calculation of the full eigenspectrum of the combined system and reservoir. Here we show that this issue can be circumvented by using a polaron transformation that maps the system into a new frame where weak-coupling theory can be applied [1]. We show that the work probability distribution is invariant under this transformation, allowing one to compute the full counting statistics of work at strong reservoir coupling. Crucially this polaron approach reproduces the Jarzynski fluctuation theorem, thus ensuring consistency with the laws of stochastic thermodynamics. We apply our formalism to a system driven across the Landau-Zener transition, where we identify clear signatures in the work distribution arising from a non-negligible coupling to the environment (see figure 1). Our results provide a new method for studying the stochastic thermodynamics of driven quantum systems beyond Markovian, weak-coupling regimes.

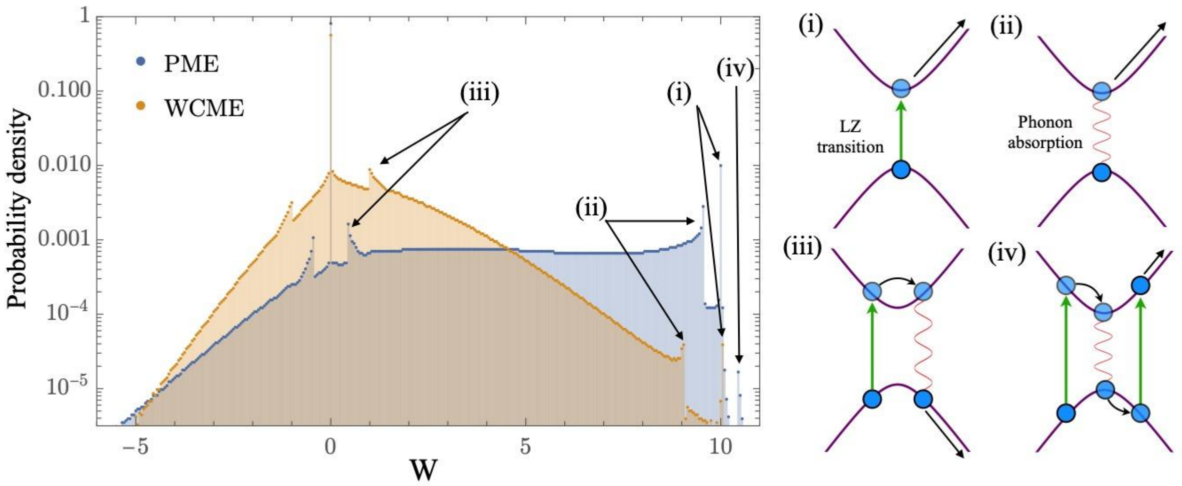

Figure 1: Probability distribution of the dissipative Landau-Zener (LZ) model as given by polaron (PME) and weak-coupling (WCME) treatments. Right: (i-iv) show the mechanisms leading to the labelled peaks in the probability distribution.

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TALK

Path Dependency in Energy Futures of Quantum Computers

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In this work, we seek to scrutinize the trajectory of quantum computer development through the lens of path dependency theory [1]. The genesis of this examination commences with a historical analysis that illuminates the power of initial choices and conditions in setting the course for technical evolution. Furthermore, this overview dissects the processes through which past decisions constrain future possibilities, thereby engendering path-dependent sequences which often lead to sub-optimal outcomes in technological progress. In this study, we expand this perspective to include practical illustrations of path dependence in technology sectors, drawing primarily on the semiconductor industry. The departure point of our analysis is informed by previous research on energy efficiency in nanocomputing paradigms [2] and the impact that path dependent decisions had on the utilization of physical-information-theoretic outcomes. The investigation underscores instances where historical contingencies have precipitated the adoption of less-than-ideal technologies as dominant designs. The objective of such an exploration is to unearth lessons that can be integrated into development of quantum computers, in order to ensure that energy future of these technologies is not unduly constrained by prior decisions and can realize their maximum potential for societal benefit.

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Thermodynamics of atom-photons interactions near resonance

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How much work is required to monitor a qubit with a coherent light source? Under which conditions are the energy exchanges between coherent light and a qubit accurately captured by quantum optical master equations?

Controlling small quantum systems using coherent light sources is a central issue in quantum technologies. In the coherent regime of driving, where a laser drives near resonant transitions in a quantum system, coherent energy exchanges occur between the laser and the system. Recent efforts were made to quantify these energy exchanges through the study of the thermodynamic consistency of the optical Bloch and Floquet master equations – which accurately describe the dynamics in the coherent regime of driving – at the average level [1] and in the steady state [2].

Here, we study the thermodynamics of near resonance atom-photon interactions at the fluctuating level. We consider a two level atom, or qubit, coupled to a driving mode and to thermal baths. Studying the statistics of the work performed on the qubit is particularly difficult when the driving is treated semiclassically: in this approach, the number of photons in the driving field is assumed to be constant, but microscopically, the energy changes induced by the bath are associated to a variation of the number of driving photons. We overcome this difficulty by starting from a microscopic description of the driving field. Using the two point measurement method with counting fields, we derive a general master equation for the joint qubit and driving mode system. In a previous work [3], we showed that, for a quantum system coupled to thermal baths, a fully thermodynamically consistent master equation (i.e., an equation ensuring the first and second laws of thermodynamics at the fluctuating level) could only be obtained by applying the secular approximation, making it impossible to study coherent energy exchanges in the steady state. Here, we generalize this result to the case where the system is also coupled to photonic coherent states, which behave like work sources. We show that the coupling with coherent states allows to derive fully consistent master equations with coherences in the steady state. We then focus on the Bloch and Floquet master equations, which are deduced from the general master equation by tracing out the driving field and performing additional approximations. We find that the Floquet master equation is fully consistent, while the Bloch equation is only consistent at the average level.

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TALK

Deep Reinforcement Learning for real-time context aware gate calibration

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Quantum control has benefited from tremendous achievements in the past few years. Calibration methods coming from physical models enabling noise cancellation (e.g., DRAG, Dynamical Decoupling) and methods based on experimental data (e.g., Process or Gate Set Tomography, Randomized Benchmarking) have been jointly used to maximize average gate fidelities. However, approaches that can achieve dynamical and contextual error robustness are still scarce [1]. In fact, some of the noise processes that may impact a quantum gate operation can yield different effects on the quantum system of interest that depend on the spatio-temporal context in which it is being applied. For example, consider the problem of calibrating a two-qubit gate between two specific qubits of a quantum processing unit containing more than two qubits. In the context of a quantum circuit, some other gates may be applied on neighboring qubits in parallel to our target gate to minimize the duration of the circuit, which could induce additional crosstalk errors to the target. The resulting output state fidelity therefore depends on the quantum channel describing the noise, but also the specific setting in which this channel applies, leading to effects on the target gate fidelity that are specified uniquely by the actual quantum circuit.

In this work, we show that those contextual effects have a non-negligible impact at the scale of a single quantum circuit, and that **context awareness** does need to be addressed **to build more reliable operations.** Secondly, we **demonstrate that model-free quantum control with Reinforcement learning (RL) [2][3] can capture this contextual dependence and provide suitable noise mitigation strategies**, that enable an adaptive pulse shaping of the same gate for each time it is applied in the circuit. We also show that although it would seem intuitive that full pulse shape design through optimal control shall be done for each gate call in the circuit [4]**, restraining ourselves to optimize the set of pulse parameters that could be tuned up in real time with state-of-the-art control systems is enough to increase circuit fidelity [5][6]**. Our approach enables the mitigation of noise coming from a quantum circuit context in a model-free manner, while significantly reducing the memory overhead related to the loading of contextual custom gate calibrations in the traditional Arbitrary Waveform Generator, which would be a bottleneck for scaling up this circuit context awareness. We moreover argue that the execution overhead related to the closed-loop optimization procedure can be further reduced by enabling the sampling of appropriate pulse parameters in real-time, leveraging advanced real-time processing features offered by advanced control systems and improve over the involved training requirements in state-of-the-art experiments [3-4][7].

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TALK

Energetic cost of quantum networks

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With the advent of the quantum age, there is significant interest in examining emerging quantum technologies in term of their security against threats, their advantages over some of their classical counterparts, but also their overall energy consumption, before planning for wide-scale implementations. While the presence of energy costs in quantum technologies, similar to classical computation, is well-known, the intricate nature of these technologies presents a formidable challenge in evaluating the total energy requirements of quantum networks.

While the energy consumption of transmitting a qubit is reduced to the cost of transporting a photon between two nodes, the energy expended in manipulating this photon at the end nodes can be considerably higher. Quantum communication setups encompass diverse techniques for creating qubits, as well as various methods for manipulating, detecting, and processing them. Additionally, achieving high-efficiency photon detection often necessitates energy-consuming cryostats.

This research focuses on modeling the energy requirements of different quantum network protocols, particularly quantum key distribution (QKD), to derive metrics such as "price-per-qubit" and "price-per-secret-key." These metrics facilitate quick comparisons of network components and communication protocols.

To accomplish this, we propose a theoretical model that estimates the energy consumption of fundamental operations involved in current quantum communication experiments, accounting for the non-trivial energy costs associated with certain classical post-processing methods. Our model is hardware dependant and relies on estimating the real energy cost, measured in the laboratory, of different sub-components of a complete experimental setup. The aim of this research work is to get a sense of the energy cost of scaling today's state of the art methods to perform communication protocols. We also provide a simulation tool, based on NetsQuid, to model and estimate the energy cost of a given experimental setup.

We apply this model to different hardware implementations of the same QKD protocol to demonstrate variation in energy consumption. These variations depend on factors such as wavelength, encoding, and post-processing techniques. By analyzing simulation results, we illustrate how these choices impact the overall energy consumption of performing a QKD protocol. Additionally, we compare the energy consumption of different QKD protocols to highlight the influence of protocol selection on the total energy cost. Furthermore, we employ our model to assess more complex network protocols envisioned for a future quantum Internet.

This work is still in preparation therefore there is no article link. The method is inspired from Marco Fellous Asiani et al, 2022 (arXiv:2209.05469) and the MNR framework proposed by Alexia Auffèves in https://doi.org/10.1103/PRXQuantum.3.020101

POSTER

General theory for the efficiency of correleted and finite-size quantum engines

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We present an exact and general theory for the performance of any quantum engine whose Hamiltonian can be written as the sum of three terms: a time-dependent and cyclic one describing the working substance, a time-independent one modelling the reservoirs, and a time-dependent interaction between them. We make no extra assumptions on the engine. We include analytical formulas for the first law of thermodynamics describing the work done by the engine, the second law of thermodynamics relating the exchange of heat and energy with entropic measures of correlations and displacements from thermal equilibrium, and a general formula for the efficiency that takes into account genuine quantum effects. In the case of a reversible engine (meaning one that is uncorrelated and in perpetual thermal equilibrium) we recover the well-known formulas of Clausius and Carnot for the second law and the efficiency, respectively. On the other hand, if the engine presents correlations or its working substance or reservoirs are not in thermal equilibrium we generalize the current results available in the literature. In particular, we study and analyse how correlations and the finite size of the reservoirs affect the general performance of the engine, such as reducing or increasing its expected efficiency. Finally, we further extend this results to heat pumps and refrigerators.

The paper is in preparation.

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POSTER

Tabletop Time-Reversibility for the Quantum Regime

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Questions to Set the Stage

Reversibility is a central concept in physics and information science, from the second law to notions of state recovery, noise and dissipation. Yet, there exists a plurality of approaches for characterizing it, some of which only apply in strictly defined, classical contexts. Given its fundamentality, a question arises: ■ can we formalize reversibility for *all* processes, classical and quantum?

This question is enhanced by a further puzzle: introducing an ancillary system, every irreversible process can always be seen as a marginal of a larger reversible global process [1]. This is sometimes called the *dilation* of a channel (as in Stinespring dilations). ■ How, then, does reversal on marginal level compare to that in the global, dilated picture? Does “reversal and marginalization commute”?

This has implications in physical implementation of recovery protocols, as this essentially translates to the question of ■ when can I reverse a process $\mathcal{R}[\mathcal{E}]$ with the same global dynamics (i.e. some unitary U) I used for the forward process $\mathcal{E}$? Formally, $\mathcal{R}\left[\mathcal{E}[\bullet] = \mathrm{Tr}_B[U(\bullet \otimes \beta)U^\dagger]\right] \overset{?}{=} \mathrm{Tr}_B[U^\dagger(\bullet \otimes \beta')U]$.

We may call this condition *tabletop time-reversibility.* Most notably, this is satisfied by Gibbs-preserving maps in *thermal operations* [2]. The question is where else does this hold? Put another way, “how special are thermal operations, with regard to reversibility?”

Responses & Results

In this work, we answer these three questions. Firstly, we adopt the perspective that the physically viable, universally applicable and axiomatically valid characterization of classical and quantum reversibility lies in Bayes’ rule and the Petz Recovery map respectively [3,4], which has been fruitful in comparing reversal across regimes and the derivation of fluctuation relations [5,6]. Doing so, we show that these fulfil very interesting intuitions about dilations and reversal. In particular, we also show that ■ reversal and marginalization (in both theories) do commute as long as one takes into propagated correlations formed between the ancillary system and the reference of the reversal. Finally, ■ we show that *tabletop time-reversibility* is a remarkably special condition, expanding on physically insightful theorems pertaining to a generalization of thermal operations, its relationship with correlations and its implications on energetics in the quantum regime.

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POSTER

IMPLICATIONS OF NONUNIFORM LEVEL SCALING FOR QUANTUM ENERGY DEVICES

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Size-invariant shape transformation is a geometric technique of continuously changing the shape of an object without altering its sizes. It allows one to separate the influences of quantum size and shape effects and to examine the pure quantum shape effects in confined systems with quantized energy levels [1]. Quantum shape effect causes peculiar thermodynamic behaviors such as spontaneous transitions into lower entropy states and cooling (heating) by adiabatic compression (expansion). The underlying physical reason for such classically impossible behaviors lies in the spectra of confined systems. We show that the geometric couplings between levels generated by the size-invariant shape transformations cause a nonuniform scaling in the spectra. We find that the nonuniform level scaling is characterized by two distinct spectral features: ground state reduction and modification of the spectral gaps (energy level splitting or degeneracy formation depending on the symmetries). A geometry-induced eigenstate swapping occurs due to the shrinkage of the eigenfunctions leading to an excessive occupation of the ground-state, which we call quantum thermal avalanche [2]. This is the underlying reason for the peculiar effect of spontaneous transitions to lower entropy states in systems exhibiting the quantum shape effect. Due to the generality of the phenomenon, the effect can be observed and applied in various quantum energy devices. Here, we will discuss its possible applications in superconducting quantum computing and in quantum heat machines. In particular, we argue that nonuniform level scaling via geometric level coupling can be exploited in Josephson junctions to reduce the thermal noise and in designing Otto-like heat engines with isoformal process opening a new dimension in thermodynamic state space. Quantum enhancements in the performance and efficiency of nanoscale energy devices can be realized due to nonuniform level scaling and quantum shape effects.

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Towards fully quantum observational entropy

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A few pages after defining the entropy that nowadays bears his name, von Neumann warns the reader that the quantity that he just defined is, in fact, unable to capture the phenomenological behavior of thermodynamic entropy [1]. More precisely, while the von Neumann entropy $S(\rho) := -\operatorname{Tr}[\rho \ln \rho]$ is always invariant in a closed system as a consequence of its invariance under unitary evolutions, the thermodynamic entropy of a closed system can instead increase, as it happens for example in the free expansion of an ideal gas. The explanation that von Neumann gives for this apparent paradox is the following: thermodynamic entropy includes not only the intrinsic ignorance associated with the microscopic state ρ of the system, but also the lack of knowledge arising from a macroscopic coarse-graining of it. The latter lack of knowledge becomes worse as the gas expands.

In recent years, von Neumann's macroscopic entropy and a generalization thereof called *observational entropy* (OE) has been the object of renewed interest [2–6]. So far, even when the narrative is based on a quantum state ρ being subject to a measurement $\mathbb{M}$, all the definitions fit in classical stochastic thermodynamics.

In this work, we explore possible fully quantum generalisations of OE. We observe that the original OE includes an implicit prior belief of the state, which is the uniform distribution. As a fully quantum generalization, we allow the observer to have a non-uniform prior described by a density operator. In this case, classical probability distributions may become insufficient to describe the non-commutativity between the state and the reference, and thus the original definition of OE is not applicable.

We have proposed four candidates for a fully quantum generalisation of OE. Qualitatively, they all describe a change of information for the process consisting in measuring a quantum state, with respect to a reference state γ. Their quantitative common features are: they recover the original definition when γ is the maximally mixed state; they have a unified expression for classical processes; and they are lower-bounded by $S(\rho)$ the von Neumann entropy.

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A Schmidt Decomposition Approach to Quantum Thermodynamics

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In this work, we address the difficulties encountered in defining the internal energy of a quantum system when studying energy exchanges in open quantum systems. This is an essential aspect of the so-called quantum thermodynamics, which claims the formulation of theoretical machinery that could be consistent for both the system of interest and its environment. Here, we show a formulation in which such consistency is naturally present and recovers the usual thermodynamic aspects of internal energy, e.g., its additivity.

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POSTER

Characterization of 4T-period time crystal on a NISQ-era quantum processor

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Time crystals, a kind of novel phase of matter which scientists have been striving to chase after, has received tremendous attention in recent years [1-4]. It spontaneously breaks time-translation symmetry which is obeyed by other matter in our day life at thermal equilibrium, such as gas, water, and ice, and it maintains the order in a constantly excited state with doubling of the driving period T. Most recently, it is claimed that time crystal has been experimentally realized on a superconducting quantum circuit by Google [5], as well as in a nuclear spin diamond system [6].

However, so far it remains unclear whether the higher order of period doubling could be realized and captured on a NISQ-era quantum processor. In this work, we propose a method on the implementation of the time evolution quantum circuit which could exhibit clear 4T-period time crystal behavior. By combining the variational quantum algorithm for quantum circuit recompilation [7-11], the Floquet time evolution is transformed to a target circuit. Compared with the conventional Suzuki-Trotter decomposition approach, our method has a much shallower circuit depth with much less CNOT gates, which is suitable for the current NISQ-era device of which the qubit error is inevitable. The 4T-period time crystal signature is therefore captured on an IBM Q quantum device, and has also been benchmarked using both the state-of-art matrix product states (MPS) for larger system size. Finally, the robustness of the 4T-period time crystal is also discussed.

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Intrinsic resource reduction via optimal fermion–qubit mappings

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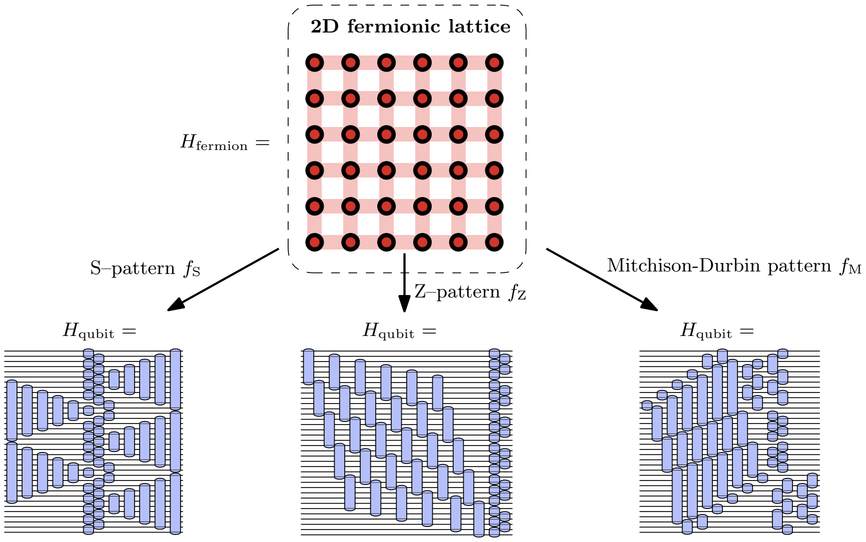
One of the most promising uses of quantum computation is simulating the behaviour of fermions, such as electrons in molecules. Quantum algorithms for these tasks are yet to see implementation at scale on today's limited quantum computers, with much focus on finding shortcuts to reduce their complexity.

We demonstrate simple coding adjustments to quantum algorithms that can improve their speed and energy costs 'free-of-charge', reducing the complexity of the program in a way that demands no additional resources in the real world. By arguing for common-sense definitions of the physical cost of a quantum simulation algorithm, we can optimise designs to consume the least of a given resource, such as physical space, clock time, or energy. For simulating some structures, such as lattices, we are able to determine the mathematically optimal setup to minimise some of these quantities.

While many have refined the latter technical stages of fermionic simulation algorithms, we turn our attention to its preliminary step: the fermion–qubit mapping, a mathematical process that encodes the unknown dynamics of fundamental particles into the quantum computer's information-carrying qubits. We invoke results in graph theory to find optimal encodings of the popular Jordan-Wigner transformation, in particular yielding blueprints for quantum computers using 13.9% less resources than existing methods for simulating square-lattice systems of fundamental particles. This result comes free-of-charge, as it simply involves strategic relabelling of particles using a mathematical trick. We argue that this strategy is applicable in studying a wide range of fundamental particles, and show that it opens a seam for novel improvements in creating sleeker blueprints for quantum computers.



Different Jordan–Wigner transformations produce qubit Hamiltonians with variable physical resource costs.

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POSTER

POWER CONSUMPTION OF A QUANTUM COMPUTER WITH SURFACE CODE-BASED LOGICAL QUBITS DEFINED ON FLIP-FLOP QUBITS IN SILICON

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Silicon qubits are evolving from research prototypes in laboratories to industry-level products [1], where scaling-up solutions are becoming imperative to realize the long-term goal of a fault-tolerant quantum computer.

Among the various types of silicon qubits published in the literature, we focus on Flip-Flop (FF) qubits. An FF qubit is conceptualized within a system composed of an electrostatically defined Quantum Dot (QD) and a phosphorous atom in a Metal Oxide Semiconductor (MOS) structure. An electric field, generated by means of a gate voltage, controls the ^{31}P bounded-electron position between the QD at the Si/SiO$_2$ interface and the ^{31}P nucleus site. The qubit's logical base states |0> and |1> are the two antiparallel spin states of electron and nucleus, where Rabi oscillations can be driven by an AC electric field through Electric Dipole Spin Resonance (EDSR). A long-range (100-500 nm) coupling between two FF qubits can be obtained by leveraging the electric dipole-dipole interaction [2] thus relaxing the stringent inter-qubit distances typical of other qubit architectures.

Using FF qubits, the energy use / power consumption is estimated for a square array hosting the logical qubit. The logical qubit is built by using one of the most promising quantum error correction codes, the surface code, that shows one of the highest error thresholds around 1% [3]. By taking into account a universal set of quantum gates obtained with analytically derived control signal sequences, an estimation of the energy use, time request and power need in a surface code cycle is provided as a function of noise level, control power and code distance.

This estimation is then utilized to derive a power-per-qubit parameter for theoretical predictions on the primary scaling-up challenges in quantum computer development. This is done by exploiting and extending a model [4] for power consumption where both the energy contribution from the cryogenic part (array of qubits, cryogenic control electronics, and cryostat) and from the room temperature section (RT electronics including heat dissipation systems) are considered and parametrized on the thermal load, geometrical size, qubit performance and architecture.

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Towards energetic optimization of quantum measurements protocols

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Quantum measurement constitutes one of the essential building blocks of most quantum information processing protocols. It is therefore crucial to precisely quantify and minimize its resource cost in realistic conditions. Important steps in this direction include fundamental bounds connecting the minimum work cost performed on the measuring apparatus to a measure of the amount of acquired information [1], however only in the ideal case of perfectly efficient measurements [2] (i.e. for which no information about the system is lost in the environment). More recently, estimates from a unitary (closed) model of the quantum measurement process showed diverging resource costs to reach the other ideal limit of projective measurement (i.e. when all the information about the measured observable is extracted) [3].

Realistic setups lead to non-ideal measurements deviating from those two limits, and are therefore expected to exhibit non-trivial tradeoffs between cost and measurement performances which are yet to be quantitatively characterized. In addition, insights about microscopic models for measuring apparatuses suggest that the apparatus must be an open (dissipative) quantum system to exhibit the observed irreversibility of the measurement-induced dynamics [4], in agreement with practically existing setups. It is therefore necessary to go beyond unitary measurement models to fully capture the process and its thermodynamic properties.

To enable the quantitative analysis of these questions, we apply tools from quantum thermodynamics to an open-system model of a measuring apparatus which can capture nonideal measurements. We exploit microscopic expressions for the second law of thermodynamics [5] to demonstrate a of previously derived lower bounds on that work cost, which relates it to the measurement performances (in particular efficiency and strength). By adding different constraints on the microscopic apparatus model (in particular in terms of available couplings and resources), we find tradeoffs between the measurement performances, the duration of the measurement and its work cost, paving the road towards systematic optimization of measurement protocols, including energetic considerations [7].

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POSTER

Optimizing quantum correlations mediated by a metasurface using reinforcement learning algorithm

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The phenomenon of superradiance or superfluorescence, which is characterized by the enhanced emission of an ensemble of quantum emitters, can be used to enable entangled multi-photon quantum light sources with applications in quantum information technologies. A key aspect of this research is designing metasurfaces that promote this behavior between distant quantum emitters with possibly uncontrolled positions and orientations. In this poster, we outline the key details of this work for the case of producing metasurfaces which enable superradiant emission of two quantum emmiters using a generalized second-order correlation function derived in *Phys. Rev. A 93, 033836*. An example of how a meta surface can influence the correlations between two dipoles can be seen below.

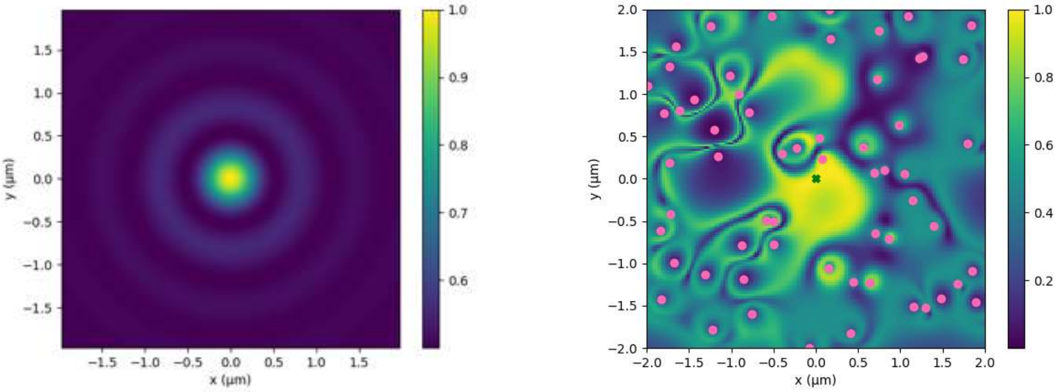

Figure 1: Plots showing the generalized second order correlation functions for (a) the case of two quantum emitters in free space and (b) the case of two quantum emitters embedded within a random assortment of dipole scatterers. The heatmap is generated by fixing one of the emitter locations at x=0, y=0 and the other dipole is scanned across the region.

The key benefits of using a reinforcement learning algorithm are that a correctly trained algorithm it is not subject to the issue that other methods are, such as particle swarm optimization which can encounter issues where it stabilizes at local minima or maxima instead of reaching optimal results. In addition to this, there is potential for the learning algorithm to produce metasurface designs more efficiently in comparison to other methods, as the learning algorithm not needing to explore as much of the action space as optimization methods due to the algorithm's prior training.

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POSTER

Which logical operations require the most resources in concatenated error-correction?

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Universal quantum computation requires the ability to implement Clifford and non-Clifford gates. While for NISQ devices, there is no significant difference in the way these gates are performed, in fault-tolerant quantum computing both type of gates require different circuits to be implemented. On one hand, the logical Clifford gates can often be implemented in a "transversal manner" which is resource-efficient in terms of physical qubits and gates. On the other hand, non-Clifford gates usually require additional ancilla qubits initialized in specific "magic-states". This preparation process is often described as costly [1–4], suggesting that it could dominate the physical resources requirements (i.e. number of physical qubits and gates) for the computer. Yet, in many quantum algorithms, the number of Clifford gates including the identity (i.e. the product Width × Depth) happens to be orders of magnitude higher than the number of non-Clifford gates [5–8]. Acknowledging this fact, it is natural to question which logical operations dominate the net physical resource overheads in an actual computation. In this work, we study this question in the context of concatenated error-correction. We show that in many cases, the total overhead for the algorithm can be fairly estimated by neglecting the non-Clifford operations, allowing to greatly simplify physical resource estimates. The fault-tolerant construction used in a quantum computers being the backbone of the architecture, these results can give insight on which logical operations are likely to consume the most energy in a computation, a crucial information in the quest to design energy-efficient quantum computers.

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POSTER

SPOQC: a Spin-Optical Quantum Computing architecture

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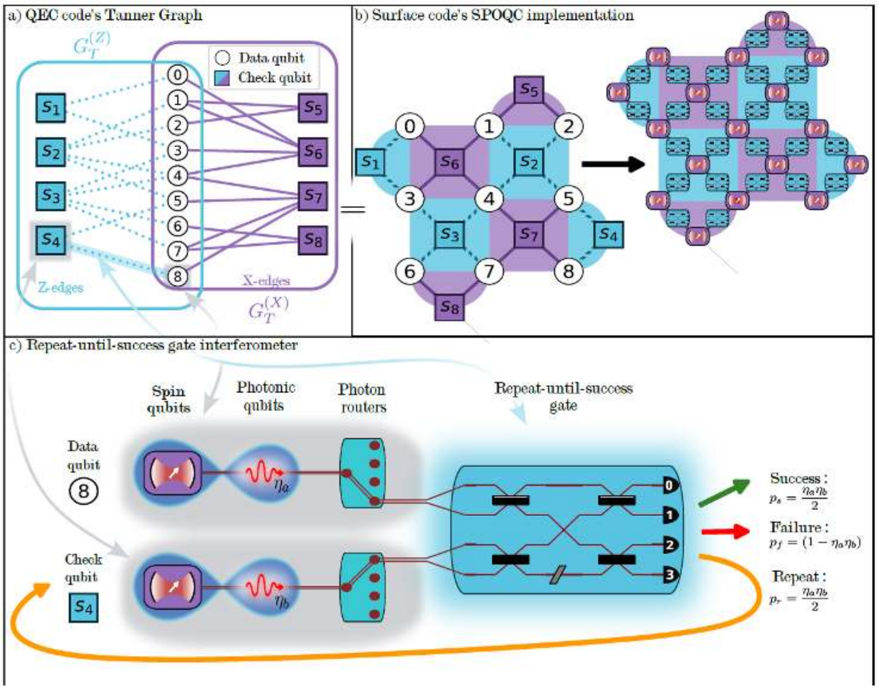

Figure: Global overview of the SPOQC architecture

A fault-tolerant quantulm computer (FTQC) can reliably execute quantum algorithms even in the presence of bounded non-negligible noise.
Achieving this without an excessively resource-intensive hardware requires a careful layout of the physical components. Photonic technology show promise for large-scale fault-tolerant quantum computing, but current efficient all-optical FTQC architectures~\cite{bartolucci2023fusion} have a large footprint because they rely on resource state generators that require extensive multiplexing. Quantum-emitter-based single-photon sources have recently outperformed probabilistic sources in single-photon quality, with their spin acting as a quantum memory, enabling entanglement with the emitted light. The current largest photonic entangled state was produced with this kind of sources~\cite{thomas2022efficient, coste2023high}.In this work, we propose the spin-optical quantum computing (SPOQC) architecture, tailored to quantum-emitter-based platforms. It significantly reduces the resource footprint and hardware complexity as it doesn't require any form of multiplexing. SPOQC's performance matches that of all-photonic architectures and is scalable and modular. Quantum information is encoded in the quantum emitters' spins, while the emitted photons enable long-range two-spin gates through repeat-until-success linear-optical gates~\cite{lim2005repeat}. This allows the implementation of advanced non-local quantum error correcting codes and itZ can also significantly reduce the algorithm's runtime. Investigating SPOQC's energetic consumption performance is a crucial future avenue for understanding its efficiency in quantum computing.

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POSTER

Engines for predictive work extraction from memoryful quantum stochastic processes

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Abstract

Quantum information-processing techniques enable work extraction from a system's inherently quantum features, in addition to the classical free energy it contains. Meanwhile, the science of computational mechanics affords tools for the predictive modelling of non-Markovian classical and quantum stochastic processes.

We combine tools from these two sciences to develop a theoretical prototype for a predictive quantum engine: a machine that charges a battery by feeding on a multipartite quantum system whose parts are temporally correlated via a classical stochastic process. In other words, the engine's fuel is a classical stochastic process with quantum outputs. We also test the engine on simple models to benchmark the performance of our engine against various alternatives, including one without coherent quantum information-processing and one without predictive functionality; our predictive quantum engine is shown to outperform these alternatives in terms of work output.

Finally, we evaluate the engine's performance on fuel processes with different degrees of temporal correlations and find the work yield to increase with such correlations. Additionally, our results suggest that there exists a phase boundary in parameter space where memory of past observations can enhance the work extraction. Our work opens the prospect of machines that harness environmental free energy in an essentially quantum, essentially time-varying form.

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POSTER

Detecting Entanglement by State Preparation and a Fixed Measurement [technical details in arXiv:2303.16368]

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One of the important contributions of quantum information theory is not only the so-called quantum advantages leading to computational speedups or higher levels of security but also the deepening of the understanding of quantum theory at the angle of fundamental physics and finding applications of quantum principles in practical tasks. In this view, quantum computing finds the usefulness of quantum dynamics that a classical counterpart cannot simulate. Measurement-based quantum computing rephrases quantum dynamics, a sequence of unitary transformations, by multipartite entangled states and local measurements. Namely, local measurements on subsystems of larger entangled states can generally demonstrate quantum dynamics.

In this work [1], we show that observables, an element in quantum theory and quantities aimed at general quantum information processing, can be estimated by quantum states and a fixed measurement. To this end, we introduce a class of states for estimation of observables, called *duplex states*, which are generally bi-separable and only of doubled number of parties of a given system. An example of a duplex state is the well-known Smolin state: its realization is also feasible with currently available quantum technologies.

We consider observables of particular interest, entanglement witnesses (EWs), that characterize the set of separable states. We construct duplex states to estimate decomposable EWs, equivalent to the partial transpose criteria. We also show duplex states for non-decomposable EWs that detect undistillable entangled states beyond the partial transpose criteria. Our construction applies to duplex states for estimating EWs for multipartite entangled states such as graph states, a resource for measurement-based quantum computing, and readily applied to distributed settings such as quantum metrology or sensor networks where multipartite entangled states are resourceful.

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Optimization and Comparison of Energetic Performance for 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 platfrom.

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 2-, 4- and 8-qubit variational quantum eigensolver (VQE) with the same success probability. 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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POSTER

Energetic Efficiency of Quantum Computing

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Quantum computing is the most prominent application of quantum technologies, which is believed to offer a computational advantage by being able to solve certain computational problems exponentially faster than classical computers. An important aspect in building new technology is the resource consumption, i.e its energy efficiency, which in the case of quantum computing is lacking consensus. The theoretical framework to address this issue is through quantum thermodynamics which provides the necessary tools to quantify and characterize the efficiency of emerging quantum technologies, and therefore is crucial in laying a roadmap to scalable devices.

Recently, it has been shown that the working mechanism of the D-Wave quantum annealers follows that of a quantum thermal machine [1]. In particular, the D-Wave chip is an open quantum system, that exchanges energy in the form heat, with the environment, and work via the external time dependent control fields. This allows the D-Wave processor to work as a thermal accelerator during a reverse-annealing protocol.

Following the recent push toward a quantum energy initiative, we have studied the thermodynamical efficiency of the D-Wave quantum annealers subject to reverse-annealing and reverse-pausing protocols. We show that pausing protocols allow to achieve better computational precision for the ground-state energy compared with reverse-annealing protocols. However, we demonstrate that this computational advantage is payed with an energy efficiency cost. Furthermore, we analyze how the topology of the D-Wave chip translates in the thermodynamics of the processor, and we show that the D-Wave chip is energetically symmetric, i.e. the thermodynamical quantities do not depend on the embedding in the graph.

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Universal Landauer-Like Inequality from the First Law of Thermodynamics

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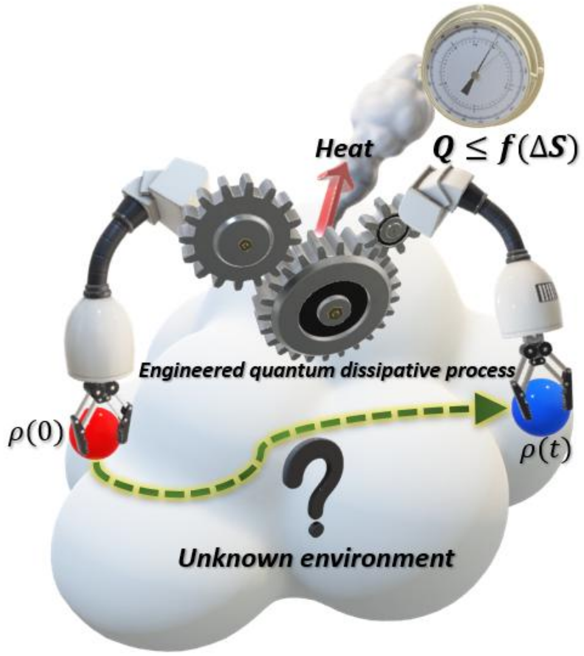
Our work introduces universal Landauer-like inequalities, establishing a robust framework for constraining energetic costs associated with quantum processes across diverse environments. These inequalities, derived from the first law of thermodynamics, offer valuable insights for researchers from diverse backgrounds – from fundamental quantum information studies to practical advancements in enabling technologies.

These universal Landauer-like inequalities [1] depend solely on system information and complement the conventional Landauer principle by providing an alternative upper bound on heat dissipation. With practical applications in mind, we demonstrate their utility in dissipative quantum state preparation and quantum information erasure scenarios. Our research unveils the transformative potential of these inequalities in the realms of quantum thermodynamics and the energetics of quantum information processing, bridging theory and practice.



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POSTER

EFFECTS OF NOISE-INDUCED COHERENCE ON THE FLUCTUATIONS OF CURRENT IN QUANTUM ABSORPTION REFRIGERATORS

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We investigate the effects of noise-induced coherence on average current [1] and current fluctuations [2] in a simple model of a quantum absorption refrigerator with degenerate energy levels. We describe and explain the differences and similarities between the system behavior when it operates in the classical regime, where the populations and coherences in the corresponding quantum optical master equation decouple in a suitably chosen basis, and in the quantum regime, where such a transformation does not exist. The differences between the quantum and the classical cases are observable only close to the maximum current regime, where the system steady state becomes nonunique. This allows us to approximate the system dynamics by an analytical model based on a dichotomous process that explains the behavior of the average current both in the classical and in the quantum cases. Due to the non-uniqueness, the scaled cumulant generating function for the current at the vicinity of the critical point exhibits behavior reminiscent of the dynamical first-order phase transition. Unless the system parameters are fine-tuned to a single point in the parameter space, the corresponding current fluctuations are moderate in the quantum case and large in the
classical case.

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POSTER

Non-Ideal Measurement Heat Engines

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We discuss the role of non-ideal measurements within the context of measurement engines by contrasting examples of measurement engines which have the same work output but with varying amounts of entanglement. Accounting for the cost of resetting, correlating the engine to a pointer state and also the cost of cooling the pointer state, we show that for a given work output, thermally correlated engines can outperform corresponding entanglement engines. We also show that the optimal efficiency of the thermally correlated measurement engine is achieved with a higher temperature pointer than the pointer temperature of the optimal entanglement engine.

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POSTER

Energetics of Optical Quantum Networks

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Quantum optical networks, which are fundamentally multiple quantum emitters interacting via propagating field modes, are integral to the transmission and manipulation of quantum information especially in distributed quantum computing and the quantum internet [1, 2]. As the scale of these networks increase, so does the importance of connecting the performance of the quantum protocol with the energy that can be measured locally in the network [3]. Indeed this can reveal the energetic cost of the protocol and the amount of energy that can be re-extracted at its end. Here we propose using the generalized notions of heat and work, i.e., bipartite-heat and bipartite-work, which account for the loss of energy due to the breaking of correlations and transfer of coherences between emitters and propagating fields respectively. Similar definitions have already been used in works such as [4, 5]. Interestingly, we find that these energetic quantities are directly and locally measurable in this optical setting as proposed in [6]. Furthermore, for a special class of fields known as Gaussian states [7, 8], we show that they have a clear operational meaning: the bipartite-work can be visualized on phase space as the displacement of the field while the bipartite-heat as its deformation. With breaking of correlations being the only source of loss of information about the states of the interacting systems, a tight bound for the second law for the quantum optical network is found using the notion of bipartite-heat.

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POSTER

Metasurface mediated long-range entanglement of quantum emitters as a future platform for quantum computing

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The study of coupled quantum emitters in the vicinity of structured photonic environments is a very active field of research. It remains a challenge, however, to accurately model and observe signatures of quantum effects in such systems. Understanding and fabricating sets ups of this kind is vital for the future of quantum computing and information. Specifically, they promise the enhancement (suppression) of physical quantities including super(sub)-radiance, and the facilitation of long-range entanglement. Only recently, super(sub)-radiance, an experimentally measurable signature of quantum correlations, was observed for the first time between distant quantum emitters using photonic crystal waveguides [1] – a milestone that permeates beyond fundamental significance. Whilst this constitutes a promising step towards applications in quantum technology, the scalability of such on-chip devices, which require precise emitter positioning, is strained at best. It is therefore desirable to consider other photonic platforms that might help to relax this constraint, and bring the ambition of having scalable quantum nanophotonics to fruition. In this regard, metasurfaces supporting collective modes provide one promising avenue, as they do not require exact positioning of emitters, therefore paving the movement to scalable flat optics devices.

In free space, two quantum emitters need to be placed at very narrow (subwavelength) separations in order to induce interactions between the two. In doing so, the emitters experience coherent and dissipative dynamics due to the effect of one emitter on the other. The presence of a medium can heavily influence interactions between quantum emitters, such that the collective parameters governing the coherent and dissipative dynamics are modified, and the emitters may then be separated by macroscopic distances. To model these systems accurately, we have derived from first principles, a rigorous quantum theory describing the dynamics of two quantum emitters located in the near-field of nanostructured environments. In particular, we have studied a nanophotonic system comprising a planar array of nanoantennas, known as a metasurface. The metasurface mediates long-range interactions via a special class of optical modes referred to as "bound states in the continuum", which can theoretically achieve infinite Q-factor. A Born-Markov master equation governs the evolution of the populations and coherences of the system; by working in the collective Dicke basis, one elicits the quantum nature of the interactions. The collective parameters for the coherent and dissipative dynamics depend on the Green function, and therefore the scattered electric field due to the metasurface. The scattered field is numerically computed using a coupled electric and magnetic dipole analytical formulation [2]. Subsequent analysis yields promising predictions on enhanced physical quantities including, but not limited to, super(sub)-radiant emission and entanglement, constituting a step towards applications in scalable quantum computation (see Figure 1). The presented theoretical framework can help in guiding experimental realizations.

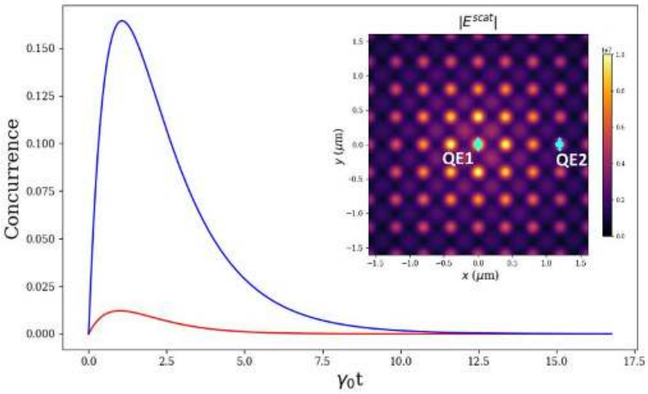

Figure 1: Concurrence as a function of time normalized against the spontaneous emission rate. The concurrence is enhanced in the presence of the metasurface (blue) compared to the free space case (red). The inset shows the scattered electric field [V/m] due to a vertical source quantum emitter (cyan) in the presence of a spherical nanoparticle array (metasurface). The target emitter is also included for illustrative purposes.

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Work extraction from unknown quantum sources

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In many realistic scenarios, experimental control is limited and only a single type of coarse-grained measurement is available to characterize a quantum state. Moreover, sources of energy are usually not fully characterized, and typically – if the energy source comes from outside, its inherent quantum state is not known. We solve the open problem of work extraction from isolated quantum systems without perfect knowledge of the initial state ensemble and with limited experimental control. In other words, we design a method that allows consistent work extraction using this limited information and limited resources (See Fig. 1). This defines a new notion of extracted work, called observational ergotropy, which measures the amount of unitarily extracted work, including the limitations of our experimental capabilities. In contrast with previous measures, observational ergotropy provides more realistic estimates and updates in accordance with our technological prowess, telling us which sources are currently the best sources of energy.

These results can be used, for example, to determine the best platform for the experimental realization of a quantum battery. This is because, as with any realistic quantum system, it cannot be fully controlled, and the state of the battery cannot be fully known, since performing the full quantum tomography is experimentally unfeasible. Our research indicates that the best experimental platforms are those with Hamiltonians which have an isolated high energy eigenvalue (meaning that there are not many other eigenvalues close to it).

Questions that I'd like to ask and discuss are: What are the types of unitary experimental control one can achieve in various platforms? Can the energy that is unitarily extracted be used to perform a useful task? In which settings is the notion of ergotropy a useful figure of merit, and in which not? Which Hamiltonians for quantum batteries are the most feasible to experimentally realize, use the true quantum advantage, and are scalable at the same time?

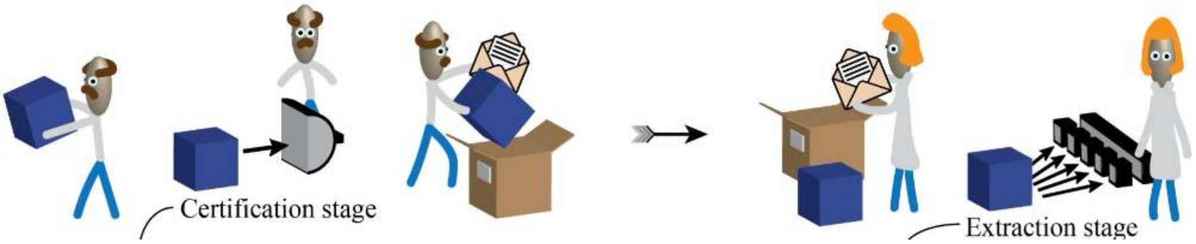

Fig. 1: An unknown quantum energy source is first certified, using limited experimental resources. Given the outcomes of these measurements, energy is unitarily extracted. Extracted energy depends on both the measurement and the energy of the source.

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POSTER

Retrodiction of a Scrambling Channel

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October 17, 2023

In the far future, Alice, a citizen of a powerful police state, wants to destroy her sensitive information. To make sure that the information will be thoroughly destroyed, she goes to a black hole and throws her information in. Unfortunately, the police state has been collecting the radiation that has been emitted by the black hole from its inception and continues to do so after Alice throws her information in. Moreover, this particular black hole is old and has radiated more than half of its mass away. Additionally, although the inside of a black hole remains inaccessible, the internal dynamics of a black hole have been solved in this future. Armed with these, the question arises: how quickly can Bob, an agent of the police state, recover the information?

Using a toy model, Hayden and Preskill showed that with these assumptions, 'old' black holes act as an 'information mirror': returning information thrown into them in a short timescale through the Hawking radiation that comes out of them. This means that if Alice puts in n qubits, Bob only needs $n + \epsilon$ qubits to recover it [1]. Since then, Yoshida and Kitaev presented an explicit protocol to recover the information from such a system [2]. This result, while originally proposed in the setting of a black hole, also applies to more lab-friendly scrambling systems such as light-atom cavities [3].

This scenario lends itself naturally to the framework of information recovery using Bayesian retrodiction. We do this by applying the Petz recovery map [4] to the scenario. We show some numerical results that the Petz map has better performance, in terms of the fidelity of the recovered information, in comparison to the protocol presented by Yoshida and Kitaev. We hope to obtain analytical results on this fidelity in the future.

(Work still in preparation)

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POSTER

Quantum Dynamic Programming

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We propose a quantum version of dynamic programming, which exponentially reduces the circuit depth of certain quantum recursive algorithms, by exponentially expanding the circuit width. Hence, our proposal provides a method to control space-time resources required for certain algorithms and thus paves a way to fully exploit a given quantum computing platform with fixed circuit width and circuit depth.

Recursive algorithms constitute a significant portion of classical algorithms. However, quantum recursive algorithms are not as central within known quantum algorithms. A potential reason for this is the circuit depth scaling that is typically exponential to the number of iterations, N. The exponential scaling originates from the naïve way of implementing recursion steps: for iteration step n, all previous iteration steps $1, \cdots, (n-1)$ are repeated multiple times – this resembles running classical algorithms without memory and thus without dynamic programming. A straightforward conversion of classical dynamic programming approaches to quantum cases is not feasible due to the no-cloning theorem, forbidding the cloning of resulting states from previous steps.

We demonstrate that the quantum dynamic programming is feasible by employing density matrix exponentiation [1], which enables us to approximately implement $\exp[i\rho t]$ given copies of a density matrix ρ and elementary gate elements that do not depend on ρ. Then, given many copies of resulting states, each recursion step, which depends on the resulting states from previous iterations, can be implemented with fixed circuit depth that does not depend on the number of previous steps. In other words, the total circuit depth scales linearly to the total number of iterations N. Finally, we obtain many copies of resulting states by running the same recursion steps parallelly with many copies of the initial states to circumvent the no-cloning restriction – this is the origin of the exponential circuit width. We explain our proposal with three example algorithms: *i)* nested fixed-point Grover search [2], *ii)* double-bracke iterations [3], and *iii)* oblivious Schmidt decomposition.

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Thermodynamic tasks in nanoscale and quantum devices exploiting nonthermal resources

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What is the prospect for exploiting nonthermal resources—possibly arising as “waste” from the operation of nanoscale and quantum devices—for further useful on-chip tasks?
On this poster, I will show examples for small-scale engines, exploiting thermoelectric properties of a conductor, that use a nonthermal distribution as a resource. A nonthermal distribution describes the occupation probabilities of states in a system, which cannot be characterized in a unique manner by a temperature and a potential. Possible useful tasks to be performed by such a resource could for example be on-chip cooling or creating charge currents (against potential biases). It can be shown that such a resource allows to do useful work without any average energy transfer between resource and working substance [1]. I will show how to characterise the performance of such a device in terms of free energy efficiencies [2,3]. I will furthermore discus some of the constraints on fluctuations in such systems - both for fluctuations in the resource [4] and for the precision of the output power [5].

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POSTER

Quantum-optimal information encoding using noisy passive linear optics

(Full version paper: arXiv:2304.12365)

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The amount of information that a noisy channel can transmit has been one of the primary subjects of interest in information theory. In this work, we analyze the optimal capacity of a large family of linear-optical quantum channels called the *thermal channels*, which can be implemented without an external energy source. A thermal channel encodes information by mixing a given input system in an energy-constrained state with the environment in some temperature and then phase-shifting it (see Fig. 1). We optimize the bound on the thermal channel capacity, quantified by Holevo information, over all encoding procedures that modulate attenuation and phase-shift of the given input state. Thermal channels are directly applicable to the task of optical quantum reading tasks [1, 2, 3, 4, 5, 6] where one probes a set of quantum channels acting as "memory cells" to decode information encoded in their parameters.

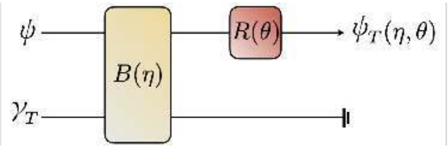

Figure 1: Thermal channel. Input "resource" state ψ with energy E is mixed with an "environment" in a thermal state γ_T by a beamsplitter $B(\eta)$ of transmittance η and then undergoes a θ phase-rotation operation $R(\theta)$, giving an output codeword state $\psi_T(\eta,\theta)$.

We show that any given input state and environment temperature, the maximum Holevo information can be achieved by an encoding procedure that uniformly distributes the channel's phase-shift parameter. Moreover for large families of input states, any maximizing encoding procedures only involve a finite number of channel attenuation values, giving codewords that form a finite number of rings around the origin in the phase space (see Fig. 2). Our result extends the aforementioned quantum reading results, which assumed a zero-temperature environment. It also gives a better understanding on optimal encoding procedures for channel information capacity on *peak* energy constraint, as opposed to *average* energy constraint which has been more extensively studied [7, 8, 9]. Lastly, a peak energy constraint is also relevant to model many practical scenarios, such as: channels with limited energy tolerance, technological limitations on generating Fock states of large occupation number, and satellite-based laser communication system where energy is scarce.

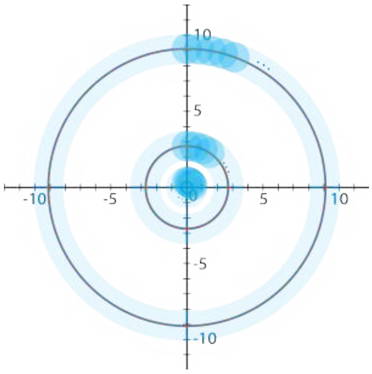

Figure 2: Phase-space visualization of codewords for an optimal encoding given coherent state resource with energy $E \sim 9.2$ and a zero-temperature environment. Radius of each red ring indicates energy of the attenuated and phase-shifted coherent state codewords (small blue circles).

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POSTER

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This work relates to the broader aim of benchmarking the purported advantages offered by quantum algorithms realizable on the NISQ devices using the Metric-Noise-Resource (MNR) framework [1]. This framework is based on (a) Metric characterizing the achievability of the task at hand, e.g. the mean square error in the ground state of a molecule predicted by VQE-UCC (b) Noise as an unavoidable *feature* of devices, and (c) Resource cost of operation. Invariably, increasing the resource input can lead to an improvement of the metric by supressing the noise, e.g. by cooling the qubits or decreasing the effect of noise, e.g. through error mitigation. However, the resources used in mitigating noise, or its effects may unavoidably lead to more noise. Therefore, the problem that the MNR framework aims to tackle is of identifying the optimally minimum amount of resource that is needed to achieve a target performance metric. As a problem mapped onto a quantum device is subject to both classical controls, e.g. for controlling temperature, as well as other hybrid artefacts such as quantum noise, crosstalk and compilation routines, they all contribute in the M-N-R spheres. Hence, the task of quantifying the resource required can be broken into resource components constituting the aforesaid spheres and their collective effect on the metric, and the interplay amongst themselves. In the long term, I plan to discover the sweet spots of maximal advantage – minimal resource through a numerical optimization over the large parameter space spanning classical controls and hybrid artefacts as mentioned above, that define the contours of such a task in quantum algorithms realizable on NISQ devices.

Here we present preliminary findings on the energetic cost of obtaining the ground state energy of a Heisenberg chain using the variational quantum eigen solver plugin in Eviden Qaptiva. Our results are based on the MNR framework described above, wherein we prepare a noise model which matches the low-level metric i.e. gate fidelity. The aforesaid noise model is then utilized to obtain the high-level metric i.e. the absolute error in the ground state energy of a Heisenberg type chain. The energetic cost is then ascertained based on the number of runs required to achieve the given high-level metric, the number of gates and other parameters suited for implementation on a superconducting qubit platform.

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POSTER

Metrology in the Presence of Thermodynamically Consistent Measurements

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Quantum metrology seeks to exploit quantum resources for the task of parameter estimation. A typical quantum metrology protocol usually involve three steps, namely, (1) initializing the system state in a pure state, (2) acquiring the unknown parameter (phase) with unitary evolution, and (3) measurement of the system to infer the unknown phase, usually a projective measurement to a pure state. Here the first and the final steps are inconsistent with the laws of thermodynamics as the preparation of a pure state requires infinite resources. Thermodynamic consistency has already impacted several other fields such as full stack quantum computation and it is natural to expect quantum metrology to be impacted by such resource constraints. Hence the realistic design of any future quantum technologies must now begin to take this into account.

It is known that thermodynamically consistent measurements can either faithfully reproduce measurement statistics of the measured system or can faithfully preserve the marginal state of the system that is correlated with a measurement device, but not both. We demonstrate that both of these varieties tremendously impact metrological tasks and produce different metrological figures of merit. We provide carefully constructed examples of popular metrological schemes and show that a judicious design choice allows us to extract good metrological sequences, whereas an imperfect measurement choice places far more stringent conditions on thermal resources. In doing so, we believe we have made substantial connection between quantum thermodynamics and quantum metrology. Therefore, we believe that our findings will have applications in realistic measurement schemes, where the noise model of measurement is modeled by finite-dimensional pointers. Such noisy realistic measurements are becoming more important as more quantum technology platforms are coming online, making our manuscript timely and relevant to a broad audience. We also discuss exceptional cases, such as infinite-dimensional pointers, in this work.

To summarise, our analysis indicates that realistic metrological tasks with thermodynamically consistent measurements fall into two categories based on whether the pointer statistics or reduced states of the system are important. These findings are helpful in designing realistic quantum metrology tasks with thermodynamically consistent resources and can guide future experimental design.

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DOI : https://doi.org/10.48550/arXiv.2304.14022

Continuous Variable multimode quantum states for quantum thermodynamics

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Quantum mechanics has introduced new concepts, such as entanglement, that can enhance the efficiency and capacity of various systems compared to their classical counterparts. In thermodynamics, a similar trend has emerged, leading to the development of the field of quantum thermodynamics. The primary aim of this field is to identify situations in which a quantum thermal machine could outperform classical machines in terms of efficiency.

Despite the potential advantages of quantum thermodynamic protocols, their implementation has typically relied on atomic and molecular systems that are difficult to stabilize and manipulate.

In order to address these challenges, we will explore the use of a photonic system with continuous variables (CV), which relies on an infinite Hilbert space. This approach offers promising avenues for implementing quantum thermodynamic protocols in a more accessible and scalable manner.

Our proposed setup involves the generation of multimode squeezed states in the frequency and time domain in the telecom regime, using a femtosecond laser to pump a non-linear waveguide in a single-pass configuration. This allows us to produce squeezed states pulse by pulse in a deterministic way. These states are detected using homodyne detection, which involves mixing the quantum signal with a local oscillator (LO) in a beam splitter. The resulting outputs are sent to photodiodes, where their relative currents are subtracted, and the resulting signal is proportional to the quadratures of the electromagnetic field. By shaping the LO with a pulse-shaping technique that involves a spatial light modulator (SLM), we can exploit the fact that homodyne detection is a projective measurement and access the different spectral modes generated in our system.

The objective of our project is to demonstrate the potential advantages of our proposed systems and their applications in the implementation of quantum thermodynamic protocols. Specifically, we aim to conduct experimental studies on two important quantum thermodynamic protocols. The first study is on the quantum battery protocol proposed by S. Seah *et al.* [1]. To accomplish this, we will use non-Gaussian states generated by mode-selective photon addition. The second study is on the thermosqueezing effect [2]. In this study, we will transfer squeezing between the modes using mode-selective beam-splitter operations.

In conclusion, quantum thermodynamics is a field with vast potential for enhancing the efficiency of thermal machines compared to classical systems. The use of photonic systems with continuous variables presents a promising solution to explore this potential. Our proposed setup utilizes multimode squeezed states generated by a femtosecond laser and detected using homodyne detection, which allows us to access different spectral modes in our system. Through experimental studies on the quantum battery protocol and the thermosqueezing effect, we aim to demonstrate the potential advantages of our proposed system and its applicability in quantum thermodynamics. The successful implementation of these protocols could pave the way for the development of more accessible and scalable quantum thermal machines.

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ABSTRACTS
for
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Variational Quantum Circuit Decoupling

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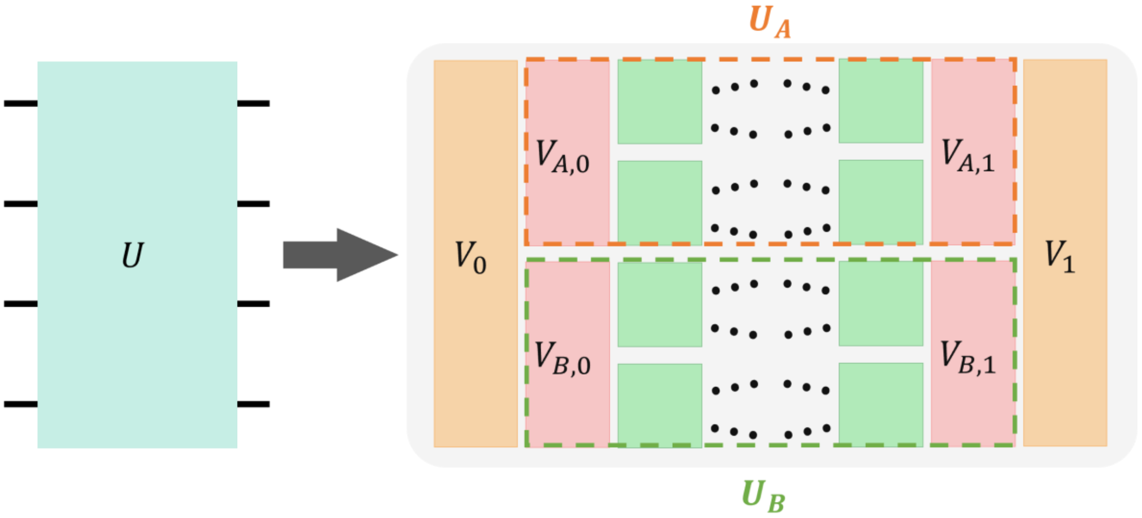
Decoupling systems into independently evolving components has a long history of simplifying seemingly complex systems. They enable a better understanding of underlying dynamics and causal structure while providing more efficient means to simulate such processes on a computer. Here we outline a variational decoupling algorithm for decoupling unitary quantum dynamics – allowing us to decompose a given n-qubit unitary gate into multiple independently evolving sub-components. We apply this approach to quantum circuit synthesis - the task of discovering quantum circuit implementations of target unitary dynamics. Our numerical studies illustrate significant benefits, showing that variational decoupling enables us to synthesize general 2 and 4-qubit gates to fidelities that conventional variational circuits cannot reach.



This decoupling of quantum circuits also enables the parallelization of the computation process. As each decoupled quantum circuit can be offloaded to a small quantum computer, this structure minimizes the runtime on the valuable large-scale quantum computer.

QYRA Flashtalk

Tabletop Time-Reversibility for the Quantum Regime

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Questions to Set the Stage

Reversibility is a central concept in physics and information science, from the second law to notions of state recovery, noise and dissipation. Yet, there exists a plurality of approaches for characterizing it, some of which only apply in strictly defined, classical contexts. Given its fundamentality, a question arises: ❶ can we formalize reversibility for *all* processes, classical and quantum?

This question is enhanced by a further puzzle: introducing an ancillary system, every irreversible process can always be seen as a marginal of a larger reversible global process [1]. This is sometimes called the *dilation* of a channel (as in Stinespring dilations). ❷ How, then, does reversal on marginal level compare to that in the global, dilated picture? Does "reversal and marginalization commute"?

This has implications in physical implementation of recovery protocols, as this essentially translates to the question of ❸ when can I reverse a process $\mathcal{R}[\mathcal{E}]$ with the same global dynamics (i.e. some unitary U) I used for the forward process $\mathcal{E}$? Formally, $\mathcal{R}\big[\mathcal{E}[\bullet] = \mathrm{Tr}_B[U(\bullet \otimes \beta)U^\dagger]\big] \overset{?}{=} \mathrm{Tr}_B[U^\dagger(\bullet \otimes \beta')U]$.

We may call this condition *tabletop time-reversibility*. Most notably, this is satisfied by Gibbs-preserving maps in *thermal operations* [2]. The question is where else does this hold? Put another way, "how special are thermal operations, with regard to reversibility?"

Responses & Results

In this work, we answer these three questions. ❶ Firstly, we adopt the perspective that the physically viable, universally applicable and axiomatically valid characterization of classical and quantum reversibility lies in Bayes' rule and the Petz Recovery map respectively [3,4], which has been fruitful in comparing reversal across regimes and the derivation of fluctuation relations [5,6]. Doing so, we show that these fulfil very interesting intuitions about dilations and reversal. In particular, we also show that ❷ reversal and marginalization (in both theories) do commute as long as one takes into propagated correlations formed between the ancillary system and the reference of the reversal. Finally, ❸ we show that *tabletop time-reversibility* is a remarkably special condition, expanding on physically insightful theorems pertaining to a generalization of thermal operations, its relationship with correlations and its implications on energetics in the quantum regime.

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Quantum sensing of phase-covariant optical channels

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Bosonic channels faithfully model a large variety of physical processes of interest in quantum optics and quantum information, ranging from the unitary phase-shift, displacement, and squeezing channels to the nonunitary thermal loss and amplification channels, phase conjugators, and additive-noise channels. Among these, the *phase-covariant* channels correspond to bath interactions that are insensitive to time translations. We investigate the optimal sensing of parameters of nonunitary phase-covariant channels using ancilla-entangled probes constrained only by total energy and the number of available modes. After establishing a general form of the optimal entangled probes for sensing such channels, we leverage recent results on the sensing of quantum-limited loss and amplification channels [1,2] to obtain analytical performance limits for sensing arbitrary phase-covariant *Gaussian* channels. The results are applied to various channel families of interest. We also obtain the limits of sensing phase-covariant channels using classically correlated probes based on laser sources and investigate the degree of achievable quantum advantage over the best classical probes. Details of our results can be found in ref. [3].

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QYRA Flashtalk

Full-stack estimates of electric power consumption of a few qubit superconducting quantum processor prototype

Khanh Uyen Giang[1], Samantha Li Xiaoyue[1], Taufiq Murtadho[1], Paul Yuanzheng Tan[1], Yung Szen Yap[2,3],
Rainer Dumke[1,2], Marek Gluza[1]

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We discuss the electricity usage estimates of key elements of superconducting qubit devices placed in cryostasts and operated using FPGAs based on an existing experimental implementations of few-qubit chips. Anticipating engineering techniques such as multiplexing we discuss the prospects for the energy usage to be similar in future large-scale quantum processors. We provide intuition on the scaling of the electric power consumption of such full-stack quantum processing units through comparisons to regular devices such as laptops or smartphones.

QYRA Flashtalk

Quantum dynamical programming for double-bracket diagonalization quantum algorithms and their prospects for advancing material science

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Double-bracket quantum algorithms allow to approach diagonalization or eigenstate preparation in quantum systems by appropriately composing evolutions under the input Hamiltonian and diagonal evolutions. We discuss how this is done, what are the bottlenecks and how quantum dynamical programming allows to run the double-bracket recursions with a polynomial runtime in the number of steps.

Within the quantum energy initiative workshop our work contributes to (3) quantum algorithms and software and its use cases may benefit the industry to perform computations for quantum materials which would be done within (4) the high performance and hybrid computing framework. Our ideas are directly applicable in existing devices which interfaces to (2) quantum hardware thanks to our research being closely informed by experimental actualities. Finally, going beyond i) state preparation we survey quantum simulation protocols for ii) extracting material properties and the necessary iii) hardware read-out needed for future material research.

How costly is Quantum Error Mitigation?

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Getting clean measurement outcomes from today's quantum computers is hindered by the noisy nature of quantum computers. There exists a whole host of quantum error mitigation methods to address this challenge. We will specifically focus on probabilistic error cancellation in this talk. Though our results indicate success, we ask, how energy-efficient is this method?

Variational Quantum Circuit Decoupling

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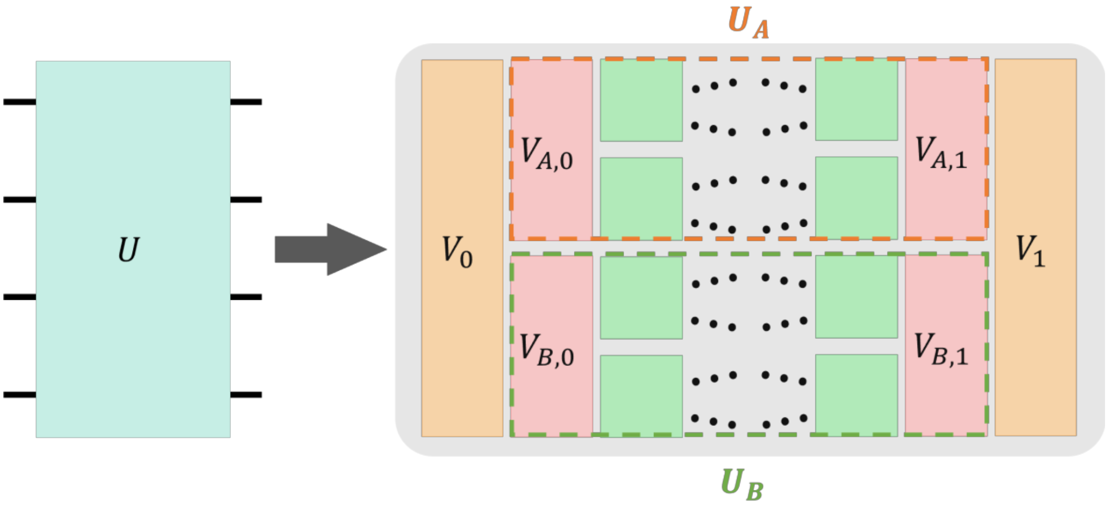
Decoupling systems into independently evolving components has a long history of simplifying seemingly complex systems. They enable a better understanding of underlying dynamics and causal structure while providing more efficient means to simulate such processes on a computer. Here we outline a variational decoupling algorithm for decoupling unitary quantum dynamics – allowing us to decompose a given n-qubit unitary gate into multiple independently evolving sub-components. We apply this approach to quantum circuit synthesis - the task of discovering quantum circuit implementations of target unitary dynamics. Our numerical studies illustrate significant benefits, showing that variational decoupling enables us to synthesize general 2 and 4-qubit gates to fidelities that conventional variational circuits cannot reach.



This decoupling of quantum circuits also enables the parallelization of the computation process. As each decoupled quantum circuit can be offloaded to a small quantum computer, this structure minimizes the runtime on the valuable large-scale quantum computer.

Achieving fault tolerance against amplitude-damping noise

Akshaya Jayashankar[1], My Duy Hoang Long[2,3], Hui Khoon Ng[2,3,4], and Prabha Mandayam[1]

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Designing fault-tolerant (FT) schemes is crucial for constructing useful quantum computers. Standard schemes typically assume no knowledge about the underlying noise in the device and rely on general-purpose error-correcting codes. These schemes are capable of tolerating arbitrary errors but require large resource overheads. Utilizing information about underlying noise in hardware for FT design may lead to better performance schemes with high threshold and low resource overheads. Recently, this noise-adapted approach is applied to construct schemes tailored to highly biased Pauli noise [1] and erasure noise [2]. These are example of Pauli noise, whose Kraus operators are Pauli operators. In our work [3, 4], we attempt to generalize this idea to non-Pauli noise models and noise-adapted codes.

In particular, we consider the *amplitude-damping* (AD) noise, which is one typical example of non-Pauli channels and is a common source of noise in many quantum computing platforms. We develop a set of encoded gadgets for universal computation, based on the Bacon-Shor code [5] and capable of tolerating multiple AD errors. We evaluate the performance of our schemes in terms of the number of physical qubits and pseudothreshold, defined as the noise strength below it, our encoded scheme enhances the accuracy of computation, over the unencoded scheme. At the lowest layer, the scheme that tolerates one AD error requires only 10 physical qubits, including ancillary qubits. At the higher layers, the scheme that tolerates t AD errors requires about $4t^2 + 6t$ physical qubits. In overall, due to the use of an adapted code, our schemes achieve a reduction in the number of physical qubits, compared to other well-known general FT schemes, e.g. the concatenated scheme based on the 7-qubit code (requires at least 3×7^t qubits) or the surface code (requires approximately $16t^2$ qubits).

In terms of pseudothreshold, the smallest scheme tolerating one AD error has the memory pseudothreshold of 1.5×10^{-4} and the computational pseudothreshold lower bounded by 2.2×10^{-5}. These numbers are smaller than the pseudothresholds estimated for the concatenated code or the surface code. In the construction of the encoded gadgets, we rely on the use Clifford gates, which convert a damping error into a Pauli error, uncorrectable by the adapted code. As a consequence, the scheme requires more qubits and more operations to protect against these propagated Pauli errors, making the FT encoded gadgets larger. This is one reason why the overall pseudothresholds are lower than expected.

Through this observation, we motivate the study of *noise-structure preserving* gates, as an important tool in developing noise-adapted FT schemes. A noise-structure preserving (NSP) gate converts a correctable error into a linear combination of correctable errors, thereby ensuring that propagated errors are still within the correction capacity of the chosen adapted code. The set of single-qubit NSP gates for AD noise is the set of rotations about z-axis. For two-qubit gates, the AD noise does not originally admit any non-trivial NSP gate. Nevertheless, we observe that by allowing error correction gadgets between code blocks to exchange syndrome bits (classical communication), it is possible to extend the set of correctable errors and hence, the set of NSP gates. One such example is the controlled-Z (CZ) gate, which may propagate a Z error, however, still correctable. We use it to construct a fault-tolerant, transversal encoded CZ gadget.

In conclusion, we have successfully demonstrated the feasibility of FT adapted to amplitude-damping noise, while highlighting some challenges. Noise-adapted FT is a necessary and promising approach towards reducing the gap between theory and realization of FT quantum computers.

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Full-stack estimates of electric power consumption of a few qubit superconducting quantum processor prototype

Khanh Uyen Giang[1], Samantha Li Xiaoyue[1], Taufiq Murtadho[1], Paul Yuanzheng Tan[1], Yung Szen Yap[2,3],
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Quantum dynamical programming for double-bracket diagonalization quantum algorithms and their prospects for advancing material science

Samantha Li Xiaoyue[1], Jeongrak Son[1], Marek Gluza[1]

[1]School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore

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