Quantum Information Days 2024
Book of Abstracts

https://qid2024.cft.edu.pl

Warszawa, October 7 – 9, 2024

Quantum Information is a rapidly developing field, attracting a large number of researchers, and leading to exciting fundamental discoveries and practical applications. The main aim of the Quantum Information Days 2024 (QID2024) workshop is to bring together young researchers working on widely understood quantum information sciences and related fields. The meeting is held in Warsaw, Poland, a lively Central European city with rich cultural and urban life.

This is a second edition of the workshop Quantum Information Days 2020(+1), which was held fully online due to the coronavirus pandemic.

NAWA NARODOWA AGENCJA WYMIANY AKADEMICKIEJ cft European Union European Social Fund NeQST

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- Wojciech Bruzda
- Jarosław Korbicz
- Owidiusz Makuta

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- Jordi Tura i Brugués (University of Leiden)
- Mário Ziman (Slovak Academy of Sciences, Bratislava)

Programme

	Monday 7th	Tuesday 8th	Wednesday 9th
8:00	Registration		
8:50	Opening		
chair:	Michał Horodecki	Alex Streltsov	Jarek Korbicz
9:00	Stefano Bosco	Jordi Tura i Brugués	Flaminia Giacomini
9:50	Razin Shaikh	Hsin-Yu Hsu	Markus Frembs
10:15	Guilherme Zambon	Mengyao Hu	Diana A. Chisholm
10:40	Coffee break		
chair:	Karol Życzkowski	Armin Tavakoli	Alessandro Candeloro
11:00	Michał Horodecki	Ana Belén Sainz	Mário Ziman
11:50	Shishir Khandelwal	Patrick Emonts	Jordi Romero i Pallejà
12:15	Alessandro Candeloro	Shubhayan Sarkar	Stanisław Kurdziałek
12:40	Lunch		
chair:	Katarzyna Roszak	Stefano Bosco	Mário Ziman
		NeQST special session: Quantum Information with Qudits	
14:30	Marko Toroš	Martin Ringbauer	Alexander Streltsov
15:20	Gábor Drótos	Armin Tavakoli	Arpan Das
15:45	Joanna Majsak	Ignacio Perito	Chenfeng Cao
16:10	Coffee break		
chair:	Soumik Bandyopadhyay	Martin Ringbauer	Wojciech Bruzda
16:30	Katarzyna Roszak	Adam Glos in place of Sabrina Maniscalco	Soumik Bandyopadhyay
17:20	Maciej Demianowicz	Marco Radaelli	Timothy Heightman
17:45	Grzegorz Rajchel-Mieldzioć	Poster Session	Closing

Invited Talks

Click on the name or scroll down to show more.

1. **Soumik Bandyopadhyay** (Italy)
2. **Stefano Bosco** (Netherlands)
3. **Flaminia Giacomini** (Austria) [online]
4. **Adam Glos** (Finland)
5. **Michał Horodecki** (Poland)
6. **Martin Ringbauer** (Austria)
7. **Katarzyna Roszak** (Czechia)
8. **Ana Belén Sainz** (Poland)
9. **Alexander Streltsov** (Poland)
10. **Marko Toroš** (England)
11. **Jordi Tura i Brugués** (Brussels)
12. **Mário Ziman** (Slovakia)

Contributed Talks

1. **Alessandro Candeloro** (Ireland)
2. **Chenfeng Cao** (Germany)
3. **Diana A. Chisholm** (United Kingdom)
4. **Arpan Das** (Poland)
5. **Maciej Demianowicz** (Poland)
6. **Gábor Drótos** (Hungary)
7. **Patrick Emonts** (Netherlands)
8. **Markus Frembs** (Germany)
9. **Timothy Heightman** (Spain)
10. **Hsin-Yu Hsu** (Taiwan)
11. **Mengyao Hu** (Netherlands)
12. **Shishir Khandelwal** (Sweden)
13. **Stanisław Kurdziałek** (Poland)
14. **Joanna Majsak** (Poland)
15. **Ignacio Perito** (Spain)
16. **Marco Radaelli** (Ireland)
17. **Grzegorz Rajchel-Mieldzioć** (Poland)
18. **Jordi Romero i Pallejà** (Spain)
19. **Shubhayan Sarkar** (Belgium)
20. **Razin Shaikh** (United Kingdom)
21. **Armin Tavakoli** (Sweden)
22. **Guilherme Zambon** (England)

Poster Authors

1. **Bihalan Bhattacharya** (Poland)
2. **Conall Campbell** (United Kingdom)
3. **Kai-Siang Chen** (Taiwan)
4. **Sambunath Das** (Czechia)
5. **Marco Fellous-Asiani** (Poland)
6. **Srijon Ghosh** (Poland)
7. **Saronath Halder** (Poland)
8. **Majid Hassani** (Netherlands)
9. **Arturo Konderak** (Poland)
10. **Mu-En Liu** (Taiwan)
11. **Paolo Luppi** (Italy)
12. **Piotr Masajada** (Poland)
13. **Hannah McAleese** (United Kingdom)
14. **Moein Naseri** (Poland)
15. **Lubashan Pathirana** (Denmark)
16. **Matthias Salzger** (Poland)
17. **Amrapali Sen** (Poland)
18. **Małgorzata Strzałka** (Czechia)
19. **Nidhin Sudarsanan Ragini** (Slovakia)
20. **Matthew Sutcliffe** (United Kingdom)
21. **Eloïc Vallée** (Netherlands)
22. **Rafael Wagner** (Portugal)

Invited Talks

1. **Soumik Bandyopadhyay** ⇑

University of Trento

Quantum State Designs and Thermalization Physics of Open Quantum Systems

Thermalization of a many-body quantum system is an intriguing property, with deep connections to other important concepts in quantum information science, such as entanglement spread, quantum information scrambling, and operator growth, among others. This makes it relevant across multiple disciplines, including quantum statistical physics, quantum information, condensed matter physics, and quantum gravity.

In the first part of this talk, we will discuss a recently introduced concept of deep thermalization, which leverages quantum chaos as a resource to construct approximate higher-order quantum state designs through measurements, a framework a.k.a emergence of quantum state t-designs. Although ubiquitous, the effects of symmetries on this phenomenon remain outstanding. Our study unveils the intricate relationship between the symmetries and measurements in constructing the approximate quantum state designs. Relying on the translational symmetry, we derive a generic sufficient condition for the measurement basis needed to obtain the designs and illustrate the deep thermalization in quantum chaotic quantum systems with symmetries.

In the latter part of the talk, we shall discuss the generalization of the celebrated Eigenstate Thermalization Hypothesis (ETH) for non-hermitian quantum systems. We demonstrate the importance of the right choice of basis to formulate this hypothesis to obtain consistent thermalization aspects found in the evolution of generic chaotic non-Hermitian systems. Finally, we shall briefly discuss a generic theoretical framework, explaining disordered averaged chaotic closed evolution through an effective Lindblad equation.

[1] Quantum **7**, 1022 (2023)

[2] Quantum **8**, 1456 (2024)

[3] `arXiv:2309.00049` (2023)

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2. **Stefano Bosco** ⇑

Delft University of Technology & QuTech

Quantum Computing with Hole Spin Qubits in Silicon and Germanium

Hole spin qubits in silicon and germanium quantum dots are rising as leading candidates for large-scale quantum computers because of their pronounced spin-orbit interactions (SOIs) and remarkable tunability, which permits efficient and ultrafast all-electric qubit control without additional components.

In this talk, I will discuss various strategies for harnessing this tunability to enhance the performance of current hole spin qubits, with a focus on both silicon and germanium qubits. One avenue of exploration involves exploiting the tunable nature of hole spin qubits to mitigate the impact of charge and hyperfine noise, which directly influences the qubit decoherence time. By identifying optimal operating conditions, referred to as sweet spots, where such noise is effectively eliminated, the performance of the qubits can be significantly improved. Moreover, charge noise presents a significant obstacle for shuttling spins, a critical requirement to establish long-range connectivity between distant qubits. Here, I will explore how SOIs can induce intricate spin dynamics that effectively filter out low-frequency noise, thereby improving the efficiency of spin shuttling processes.

Furthermore, the influence of SOIs extends to two-qubit gates, where exchange anisotropies, induced by these interactions, offer avenues for accelerating the execution of two-qubit gates without compromising fidelity. This implies that by leveraging the unique properties of SOIs, novel methods can be devised to expedite gate operations, paving the way towards large-scale spin-based quantum information processing.

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3. **Flaminia Giacomini** ⇑

SNSF Ambizione Fellow, ETH Zürich

Quantum Effects in Gravity from a Delocalised Quantum Source

Understanding the fundamental nature of gravity at the interface with quantum theory is a major open question in theoretical physics. Recently, the study of gravitating quantum systems, for instance a massive quantum system prepared in a quantum superposition of positions and sourcing a gravitational field, has attracted a lot of attention: experiments are working towards realising such a scenario in the laboratory, and measuring the gravitational field associated to a quantum source is expected to give some information about quantum aspects of gravity. However, there are still open questions concerning the precise conclusions that these experiments could draw on the nature of gravity, such as whether experiments in this regime will be able to test more than the Newtonian part of the gravitational field.

In my talk, I will present a new result, where a delocalised quantum source gives rise to effects that cannot be reproduced using the Newton potential nor as a limit of classical General Relativity. These effects can in principle be measured by performing an interference experiment, and are independent of graviton emission.

Identifying stronger quantum aspects of gravity than those reproducible with the Newton potential is crucial to prove the nonclassicality of the gravitational field and to plan a new generation of experiments testing quantum aspects of gravity in a broader sense than what proposed so far.

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4. **Adam Glos (in place of Sabrina Maniscalco)** ⇑

Algorithmiq Ltd

Treespilation and the Bonsai Algorithm: Grow and Trim your own Fermion-to-Qubit Mappings

Quantum computers hold great promise for efficiently simulating Fermionic systems, benefiting fields like quantum chemistry and materials science. To achieve this, algorithms typically begin by choosing a Fermion-to-qubit mapping to encode the Fermionic problem in the qubits of a quantum computer. The mapping transforms a local problem in Fermionic space into a non-local one in the qubit space, resulting in deep circuits, particularly on current quantum computers with limited qubit connectivity.

In the recent works by Algorithmiq, we propose an algorithm for designing flexible fermion-to-qubit mappings using ternary trees. We explore the relationship between the structure of these trees and key properties of the resulting mapping, such as Pauli weight and mode occupation delocalization. We demonstrate how well-known mappings like Jordan-Wigner, Parity, Bravyi-Kitaev, and ternary-tree mappings fall into this formalism and introduce the Bonsai algorithm for generating mappings tailored to the limited hardware connectivity. When applied to Heavy-Hexagon layouts, the algorithm achieves favourable Pauli weight scaling of square root of the number of qubits. Building upon this, we present treespilation, which is a method for optimizing the mapping based on the Fermionic representation of the state we want to implement on the quantum computer and the desired transpilation scheme.

We demonstrate its effectiveness by reducing the CNOT gate counts needed for simulating chemical ground states found with ADAPT-VQE, achieving significant reductions, up to 74%, on fully connected systems. We observe similar reductions on devices with limited qubit connectivity like IBM Eagle chips, with CNOT counts in certain instances surpassing those initially achieved on fully connected devices. Broadly speaking, these results show that the formulation of the problem – in this case a Fermionic problem – with the transpilation scheme in mind benefits the overall transpilation procedure.

5. **Michał Horodecki** ⇑

University of Gdańsk

Catalytic Advantage in Otto-Like Two-Stroke Quantum Engines

We demonstrate how to incorporate a catalyst to enhance the performance of a heat engine. Specifically, we analyze efficiency in one of the simplest engines models, which operates in only two strokes and comprises of a pair of two-level systems, potentially assisted by a d-dimensional catalyst. When no catalysis is present, the efficiency of the machine is given by the Otto efficiency. Introducing the catalyst allows for constructing a protocol which overcomes this bound, while new efficiency can be expressed in a simple form as a generalization of Otto's formula. The catalyst also provides a bigger operational range of parameters in which the machine works as an engine.

Although an increase in engine efficiency is mostly accompanied by a decrease in work production (approaching zero as the system approaches Carnot efficiency), it can lead to a more favorable trade-off between work and efficiency. The provided example introduces new possibilities for enhancing performance of thermal machines through finite-dimensional ancillary systems.

[1] Phys. Rev. Lett. **132**, 260403 (2024)

[2] arXiv:2402.10384 (2024)

6. **Martin Ringbauer** ⇑

University of Innsbruck

Quantum Computing and Simulation with Qudits

Current quantum computers and simulators are almost exclusively built for binary information processing, yet the underlying hardware almost always natively supports multi-valued logic. I will discuss the opportunities and challenges such an approach opens up in a trapped ion platform and the extent to which it can help improve quantum information processing. This will be exemplified with recent experimental result for qudit-enhanced QIP, as well as native qudit quantum simulations.

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7. Katarzyna Roszak ⇑

Czech Academy of Sciences

Transfer and Teleportation of System-Environment Entanglement

We study bidirectional teleportation while explicitly taking into account an environment [1]. This environment initially causes pure dephasing decoherence of the Bell state which assists teleportation. We find that when teleportation is performed in one direction it is accompanied by a transfer of correlations into the post-teleportation state of qubit C, which results in decoherence of the state. In the other direction, if no new decoherence process occurs, we find that not only the state of the qubit but also its correlations with an environment are being teleported with unit Fidelity. These processes do not depend on the measurement outcome during teleportation and do not differentiate between classical and quantum correlations. If, on the other hand, the second teleportation step is preceded by decoherence of the Bell state then the situation is much more complicated. Teleportation and transfer of correlations occur simultaneously, yielding different teleported qubit-environment states for different measurement outcomes. These states can differ in the degree of coherence of the teleported qubit, but only for an entangling Bell-state-environment interaction in the first step of teleportation, can they have different amounts of qubit-environment entanglement. In the extreme case, one of the teleported qubit states can be entangled with the environment while the other is separable.

We find that the decoherence effects from the first step can be suppressed during the second quantum teleportation. This effect is probabilistic and works only for certain measurement outcomes in the teleportation procedures. The effect is purely quantum and most pronounced for qubit systems, where in 25% of instances the decoherence can be reversed completely [2].

[1] Phys. Rev. A **105**, 012407 (2022)

[2] Quantum **7**, 923 (2023)

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8. **Ana Belén Sainz** ⇑

University of Gdańsk

Activation of Post-Quantum Steering

In this talk we will discuss the phenomenon of Einstein, Podolsky, and Rosen (EPR) steering, and its relation to Bell nonclassicality. We will focus on the so-called non-signalling resources (those that could in principle be achieved in non-signalling theories) in both Bell and EPR experiments, in particular those which cannot be realised with a quantum setup (called post-quantum). Previous work shows how EPR scenarios allow for postquantum resources which, from the viewpoint of the associated Bell scenario, generate only correlations compatible with quantum theory.

In this talk we will see how one can activate the post-quantumness of such EPR resources by placing them in a larger Bell-like network, so that the observed correlations may violate a Bell inequality beyond what's possible in a quantum experiment. That is, we will show how to activate post-quantum steering so that it can now be witnessed as post-quantum correlations in a Bell scenario.

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9. **Alexander Streltsov** ⇑

Institute of Fundamental Technological Research PAS

Catalysis of Quantum Entanglement and Entangled Batteries

We discuss recent progress on entanglement catalysis, including the equivalence between catalytic and asymptotic transformations of quantum states and the impossibility to distill entanglement from states having positive partial transpose, even in the presence of a catalyst. A more general notion of catalysis is the concept of entanglement battery. In this framework, we show that a reversible manipulation of entangled states is possible. This establishes a second law of entanglement manipulation without relying on the generalized quantum Stein's lemma.

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10. Marko Toroš ⇑

University College London

Rotationally Induced Quantum Non-Locality

Many phenomena and fundamental predictions, ranging from Hawking radiation to the early evolution of the Universe rely on the interplay between quantum mechanics and gravity or more generally, quantum mechanics in curved spacetimes. However, our understanding is hindered by the lack of experiments that actually allow us to probe quantum mechanics in curved spacetime in a repeatable and accessible way.

In this talk we review recent results of quantum optics on rotating platforms that are forming the link between theoretical ideas about the quantum gravity interface and the current experimental realities. Such experiments can no longer be explained in a Newtonian picture of the world, but rather require the introduction of Einsteinian notions or relativity. We will discuss how ostensibly quantum phenomena can be controlled with low-frequency mechanical rotations using a coupling arising from the underlying spacetime metric. The experimental data conclusively shows that low-frequency mechanical rotations affect the bunching behaviour of photon pairs [1], and can transform photons from perfectly indistinguishable (bosonic behaviour), to perfectly distinguishable (fermionic behavior) [2,3].

Furthermore, we predict the generation of intraparticle entanglement with low frequency mechanical rotations [4], and of rotationally-induced quantum non-local entanglement, which can maximally violate the Bell-Clauser-Horne-Shimony-Holt inequality in an experimentally accessible regime [5].

[1] Phys. Rev. Lett. **123**, 110401 (2019)

[2] Phys. Rev. A **101**, 043837 (2020)

[3] Phys. Rev. Research **5**, L022005 (2023)

[4] Phys. Rev. Lett. **129**, 260401 (2022)

[5] `arXiv:2407.14276` (2024)

11. Jordi Tura i Brugués

⇑

Leiden University

Certifying Spectral Gaps of Quantum Many-Body Systems

In this presentation, I will explore the challenges and methodologies associated with proving the presence of spectral gaps in quantum many-body systems, with a focus on the 1D AKLT model. Spectral gaps are central in our understanding of physical properties, such as ground state structure and correlation laws. In addition, spectral gaps are of direct importance in quantum computing, as they indicate how efficient an adiabatic quantum computation can be with provable guarantees of success.

We introduce two innovative constructions based on semidefinite programming (SDP) aimed at local, frustration-free, and translation-invariant Hamiltonians. The first employs positive operator decompositions to obtain translation invariant operators, enhancing the accuracy of the gap's lower bound with increased operator support size. The second utilizes the moment matrix method for a tighter lower bound through sum-of-squares decompositions involving non-commuting variables represented as Pauli operators.

Furthermore, I will discuss the role of SU(2) symmetries in simplifying the problem via Schur-Weyl duality, leading to significant computational efficiency improvements. This approach not only advances our understanding of quantum systems but also serves as a precursor for practical applications, such as the adiabatic preparation of tensor network states, by providing a reliable method to certify spectral gaps.

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12. **Mário Ziman** ⇑

Slovak Academy of Sciences

Storing Quantum Dynamics

I will review the results on "quantum learning", i.e., the art of storing quantum dynamics in states of quantum systems and the later retrieval of their action. I will describe the optimal solutions for approximate and probabilistic versions of this tasks, focused on the case of unitary gates.

Further we will discuss the consequences for quantum programmability and noise robustness of the "retrieving machines".

Contributed Talks

1. Alessandro Candeloro ⇑

Trinity College Dublin

Intersubjectivity with Finite Resources

Recent investigations have demonstrated that achieving ideal measurements generally requires an infinite allocation of resources, typically for cooling down the pointer [1]. In this contribution, we adopt a broader perspective, focusing on the emergence of intersubjectivity as a model for measurement processes. Intersubjectivity corresponds to a scenario where multiple observers all agree on the observed outcome (agreement), and the local random variable reproduces exactly the original random variable for the system observable (probability reproducibility) [2]. This framework also includes invasive measurements, which are often overlooked in discussions related to the emergence of objectivity, including Quantum Darwinism [3] and operational objectivity [4]. For an ideal process, a theorem by Ozawa shows that agreement and reproducibility are mutually implied [2].

In this talk, we explore this scenario under the constraint of finite thermodynamic resources [5]. Our goal is to elucidate the interplay between agreement, properly quantified, and the challenge imposed by the impossibility of pure state preparation, a situation typically associated with the third law of thermodynamics [6]. We show that if the latter holds, then agreement and local reproducibility condition cannot be exactly satisfied. We define a set of quantities that measure the deviation from intersubjectivity given the initial non-full-rank state preparation, and we identify a form of coarse-grained purity as the quantity that controls this deviation.

Our study reveals that the only way to achieve agreement, and thus intersubjectivity, is via pure state preparation. From this, we conclude that attaining intersubjectivity in a measurement process, even in disturbing ones, requires an infinite amount of resources.

Eventually, we also establish connections to Landauer's erasure equality [7], specifically addressing the heat dissipation and entropy production during such a measurement process. Our results provide a link between quantum thermodynamics and the foundation of quantum measurement and intersubjectivity.

[1] Quantum **4**, 222 (2020)

[2] `arXiv:1911.10893` (2019)

[3] Rev. Mod. Phys. **75**, 715 (2003)

[4] Quantum **5**, 571 (2021)

[5] in preparation

[6] PRX Quantum **4**, 010332 (2023)

[7] New J. Phys. **16** 103011 (2014)

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2. Chenfeng Cao ⇑

Freie Universität Berlin

Exploiting Many-Body Localization for Scalable Variational Quantum Simulation

Variational quantum algorithms have emerged as a promising approach to achieving practical quantum advantages using near-term quantum devices. Despite their potential, the scalability of these algorithms poses a significant challenge. This is largely attributed to the "barren plateau" phenomenon, which persists even in the absence of noise.

In this work, we explore the many-body localization (MBL)-thermalization phase transitions within a framework of Floquet-initialized variational quantum circuits and investigate how MBL could be used to avoid barren plateaus. The phase transitions are observed through calculations of the inverse participation ratio, the entanglement entropy, and a metric termed low-weight stabilizer Rényi entropy. A critical element of our study involves the experimental validation of the phase transitions using the 127-qubit `ibm_brisbane` quantum processor. By initializing the circuit in the MBL phase and employing an easily preparable initial state, we find it is possible to prevent the formation of a unitary 2-design, resulting in an output state with entanglement that follows an area – rather than a volume-law, and which circumvents barren plateaus throughout the optimization. Utilizing this methodology, we successfully determine the ground states of various model Hamiltonians across different phases and show that the resources required for the optimization are significantly reduced.

These results provide new insights into the interplay between MBL and quantum computing and suggest that the role of MBL states should be considered in the design of quantum algorithms.

[1] arXiv:2404.17560 (2024)

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3. Diana A. Chisholm ⇑

Queen's University Belfast

Distinguishing Between Redundancy and Consensus when Quantifying Quantum Objectivity

We give rigorous definitions of "redundancy" and "consensus", two different measures of the degree of objectivity of quantum states, with clear operative interpretations that reflect their meaning in the English language. Although the two terms are often used interchangeably in discussions on quantum objectivity, they actually represent distinct concepts that capture different aspects of the quantum to classical transition.

Moreover, the key frameworks employed in the study of quantum objectivity, namely spectrum broadcast structure and quantum Darwinism, naturally arise from these measures. While discussing the differences between redundancy and consensus, and their usefulness in interpreting the degree of objectivity of quantum states, we will employ them to show that, in the framework of quantum Darwinism, failing to use the averaged mutual information can lead to misleading results.

Our framework offers a fresh perspective for interpreting both current and future findings in the realm of quantum objectivity and, consequently, the emergence of classical behavior from the quantum domain.

[1] Quantum **7**, 1074 (2023)

[2] arXiv:2401.04769 (2024)

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4. **Arpan Das** ⇑

University of Warsaw

Universal Time Scalings of Sensitivity in Markovian Quantum Metrology

Assuming a Markovian time evolution of a quantum sensing system, we provide a general characterization of the optimal sensitivity scalings with time, under the most general quantum control protocols. We allow the estimated parameter to influence both the Hamiltonian as well as the dissipative part of the quantum master equation. We focus on the asymptotic-time as well as the short-time sensitivity scalings, and investigate the relevant time scales on which the transition between the two regimes appears. This allows us to characterize, via simple algebraic conditions (in terms of the Hamiltonian, the jump operators as well as their parameter derivatives), the four classes of metrological models that represent: quadratic-linear, quadratic-quadratic, linear-linear and linear-quadratic time scalings.

We also provide universal numerical methods to obtain quantitative bounds on sensitivity that are the tightest that exist in the literature.

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5. **Maciej Demianowicz** ⇑

Gdańsk University of Technology

Completely Entangled Subspaces of Entanglement Depth k

Entangled subspaces are an important concept in quantum information science, holding both theoretical and practical significance. In this talk, I will discuss the new notion of completely entangled subspaces of entanglement depth k (k-CESs). These are subspaces of n-partite Hilbert spaces containing only pure states with an entanglement depth of at least k. They generalize the notion of "standard" completely entangled subspaces, recovering them for $k = 2$, while for $k = n$ giving the so-called genuinely entangled subspace (i.e., subspaces composed solely of genuinely multipartite entangled pure states).

In this talk, I will discuss several topics related to k-CESs, including their universal construction, detection, and relation to unextendible product bases.

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6. **Gábor Drótos** ⇑

HUN-REN Institute for Nuclear Research

Certifying Non-Projective Measurements and a Complex Hilbert Space in a Qubit Prepare-and-Measure Scenario: How Self-Testing Helps

Self-testing is a promising theoretical approach to certifying, e.g., specific quantum states and measurements, which we refer to as targets. Originally, it relied solely on the outcome statistics of the measurements involved in a device-independent setup. We turn to a semi-device-independent setup by considering a prepare-and-measure scenario for qubit messages.

We construct linear witnesses (i.e., linear functionals on the outcome statistics of the measurements) for performing self-tests in possibly minimal setups within this scenario. In a setup involving four (three) preparations and three (two) projective measurements in addition to the target, we exemplify how to self-test any four- (three-) outcome extremal positive operator-valued measure. We also achieve self-testing of configurations of any number of pure state preparations with the help of three projective measurements at most.

However, self-testing in a strict sense is a purely theoretical tool, since it can only certify perfect agreement with the target. A relaxation is to certify only a single but well-defined property of the configuration of preparations or that of the relevant measurement.

In this spirit, we provide a means to certify that a set of four prepared states spans a complex qubit Hilbert space. For this purpose, we introduce a specific complex configuration of four qubit states, and design a linear witness for self-testing this set in a minimal setup.

We then determine the maximum value attainable by evaluating the so-defined witness for any real configuration of four qubit preparations. Then should we perform an experiment and evaluate the witness to exceed that maximum, the complex nature of the Hilbert space spanned by the actual preparations becomes certified. We expect such a certification scheme to be useful for preparations that are intended to implement the set of states targeted by the design of the witness but which are subject to experimental noise.

In a similar way, we can also certify that an actual measurement is non-projective, with the help of a witness constructed for self-testing a specific non-projective measurement (which we choose to be related to the above-mentioned configuration as an example). We introduce a two-variable witness space to enhance the power of such a certification.

To illustrate these ideas experimentally, we implemented prepare-and-measure scenarios for self-testing configurations of the above-mentioned type and the related non-projective measurements as quantum circuits on publicly available quantum processors of IBM and IonQ. Experimental witness values exceeded the relevant maxima in many cases. Thereby, we successfully certified the existence of a complex qubit Hilbert space in our experiments, as well as the non-projective nature of a qubit measurement performed on them.

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7. Patrick Emonts ⇑

Leiden University

Detecting Bell Nonlocality in Superconducting Devices

Quantum nonlocality describes a stronger form of quantum correlation than that of entanglement [1]. It refutes Einstein's belief of local realism and is among the most distinctive and enigmatic features of quantum mechanics. It is a crucial resource for achieving quantum advantages in a variety of practical applications, ranging from cryptography and certified random number generation via self-testing to machine learning. While the few-body case is well-explored, the detection of nonlocality especially in quantum many-body systems, is notoriously challenging.

In this talk, I first motivate the usage of energy as a detector for many-body Bell nonlocality [2–3] and the certification of Bell correlation depth [4]. If an appropriate Hamiltonian is chosen, it can be used as a Bell correlation witness and by variationally decreasing the energy of a many-body system across a hierarchy of thresholds, we certify an increasing Bell correlation depth from experimental data.

In a recent work [5], we show that this theoretical concept is experimentally viable. We report an experimental certification of genuine multipartite Bell correlations, which signal nonlocality in quantum many-body systems, up to 24 qubits with a fully programmable superconducting quantum processor.

As an illustrating example, we variationally prepare the low-energy state of a two-dim. honeycomb model with 73 qubits and certify its Bell correlations by measuring an energy that surpasses the corresponding classical bound with up to 48 standard deviations. Our results establish a viable approach for preparing and certifying multipartite Bell correlations, which provide not only a finer benchmark beyond entanglement for quantum devices, but also a valuable guide towards exploiting multipartite Bell correlation in a wide spectrum of practical applications.

[1] Rev. Mod. Phys. **86**, 419 (2014)

[2] Phys. Rev. X, **7**, 021005 (2017)

[3] `arXiv:2405.14587` (2024)

[4] Phys. Rev. D **35**, 3066 (1987)

[5] `arXiv:2406.17841` (2024)

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8. Markus Frembs ⇑

Leibniz University Hannover

Entanglement and the Arrow of Time

Quantum correlations in general and quantum entanglement in particular embody both our continued struggle towards a foundational understanding of quantum theory, as well as its advantage over classical physics in various information processing tasks. Consequently, the problems of classifying (i) quantum states from more general (non-signalling) correlations, and (ii) entangled states within the set of all quantum states are at the heart of quantum (information) theory.

In my talk, I will present two recent results that shed new light on these problems, by revealing a deep connection with time in quantum theory. First, in [1] a solution to problem (i) is obtained for the bipartite case. I will sketch this result, focussing on a crucial physical insight: quantum states preserve so-called time orientations – roughly, the unitary (or anti-unitary) evolution of the respective physical system. Second, [2] proves that time orientations are intimately related to quantum entanglement: a bipartite quantum state is separable if and only if it preserves arbitrary time orientations in local subsystems. This provides a novel solution to problem (ii).

I will touch on various implications of these results, including for the reconstruction programme of quantum theory from physical or information-theoretic principles, as well as for the framework of quantum causality. From a more mathematical perspective, I will further highlight how these results reveal an often neglected distinction between different algebraic levels on which the Choi-Jamiołkowski isomorphism operates, specifically the level of Jordan as opposed to that of C^*-algebras [3]. I will point out how this distinction underlies the issue of basis-independence in Choi's most commonly used version of the isomorphism, and argue for a basis-independent variant without spoiling channel-state duality.

[1] Phys. Rev. A **106**, 062420 (2022)

[2] Phys. Rev. A **107**, 022218 (2023)

[3] J. Phys. A: Math. Theor. **57** 265301 (2024)

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9. **Timothy Heightman** ⇑

ICFO

Solving Quantum Many-Body Unitary Dynamics with Neural ODEs

The ability to characterise many-body Hamiltonians is central in constructing quantum information and processing technologies. At the hardware level, optimal control of platforms such as trapped ions, neutral atoms, and photonic technologies rely on the design and implementation of pulses, constructed through accurate knowledge of the underlying Hamiltonian generating dynamics of may-body physical systems. Obtaining accurate knowledge of the underlying Hamiltonian is thus instrumental in the implementation of quantum information processing tasks. This constitutes the Hamiltonian Learning (HL) problem – the task of finding the underlying Hamiltonian of some unitary process by learning from pairs of input output states (trajectories). Existing literature explores HL through a range of approaches that have made it possible to learn quadratic Hamiltonians, at best, with a sub-linear number of learnable coefficients. Such a limitation makes HL thus far infeasible as a practical tool for error mitigation, device certification, and reliable optimal control. We propose a novel method for the HL problem which uses Neural Ordinary Differential Equations (NODEs), combined with an ansatz Hamiltonian which can perform Hamiltonian learning on systems previously unlearnable in the literature.

Our method is reliably convergent, showing correct dynamics well beyond training times as well as being experimentally friendly, using bitstrings from marginal distributions of compatible observables as its training data. We can also use NODEs to return a numerical estimate for the ground truth via a curriculum learning procedure, providing crucial interpretability with deep learning methods. Finally, we benchmark our method on previously unlearnable Hamiltonians from the many-body literature, such as the Anisotropic Heisenberg Hamiltonian, the PXP Hamiltonian from quantum many-body scars, and higher-order interactions than quadratic. Code for our method is available and open source.

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10. Hsin-Yu Hsu ⇑

National Cheng Kung University

Symmetric and Asymmetric Strategies for Bell-Inequality Violation

In quantum information, asymmetry, i.e., the lack of symmetry, is a resource allowing one to accomplish certain tasks that are otherwise impossible. In a Bell test using any given Bell inequality, the maximum violation achievable using quantum strategies that respect or disregard a certain symmetry can be different. When a gap is present, a quantum violation beyond the symmetric bound immediately witnesses the asymmetry in the underlying quantum strategies.

Here, we focus on bipartite Bell scenarios and the symmetry of permutation invariance possessed by identical quantum particles. In particular, we provide evidence showing that the family of symmetric Collins-Gisin-Linden-Massar-Popescu inequalities can always be maximally violated by symmetric quantum strategies minimal in the Hilbert space dimension. However, the same cannot be said for certain Bell inequalities with more inputs. For instance, we have identified examples of symmetric Bell inequalities maximally violated by a two-qubit state, but whose violation becomes suboptimal if we further impose that the strategies are permutational invariant. This means that we can trade Hilbert space dimension for asymmetry when maximizing a Bell violation or equivalently, the winning probability of some generalized nonlocal game.

Our findings also suggest that for any Bell inequality, one can find a relabeled version that cannot be violated by symmetric quantum correlations. In other words, whenever a quantum strategy violates such an inequality, we can immediately conclude, in a device-independent manner, that the underlying quantum strategy cannot be permutationally invariant.

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11. Mengyao Hu ⇑

Leiden University

Optimizing Bell Inequalities via Tensor Network Contractions in Tropical Algebra

Nonlocality is one of the key features of quantum physics, which is revealed through the violation of a Bell inequality. In large multipartite systems, nonlocality characterization quickly becomes a challenging task. A common practice is to make use of symmetries, low-order correlators, or exploiting local geometries, to restrict the class of inequalities we are investigating [1–2].

Tropical algebra, where the sum is replaced by the minimum and the product is replaced by the arithmetic addition, is an adequate framework for discrete optimization problems. For Bell inequalities in one-dimensional infinite, translationally invariant (TI) systems, we introduce how to find their corresponding tensors and optimize these inequities using tensor network contractions in tropical algebra.

We establish a connection between the notions of tropical eigenvalue and the classical bound per particle as a fixed point of a tropical tensor renormalization procedure [3]. Additionally, we find that the tropical eigenvector can be utilized to list all the vertices of the corresponding local polytope. We establish a connection between the so-called critical graph and the vertex and facet information of the projected local polytope. This allows us to efficiently compute and encode the optimal local deterministic strategies, thereby providing a tool to assess the tightness of a given Bell inequality. We demonstrate that employing a tensor network formalism within the context of tropical algebra provides an effective framework for optimizing Bell inequalities.

[1] Phys. Rev. X **7**, 021005 (2017)

[2] Phys. Rev. Lett. **118**, 230401 (2017)

[3] `arXiv:2208.02798` (2022)

12. Shishir Khandelwal ⇑

Lund University

Maximal Steady-State Entanglement in Autonomous Quantum Thermal Machines

It is well-known that failure to isolate a quantum system leads to its decoherence. However, quantum thermal machines offer an interesting perspective on this common wisdom: these are systems that explicitly use spontaneous interactions with the environment to perform a task. For these quantum systems, the environment is not detrimental but a resource. A basic conceptual question is therefore whether a quantum thermal machine, which uses no source of work, external driving or time-coherent control, can generate the strong forms of quantum coherence exclusively from spontaneous interactions with large classical reservoirs.

It was shown in an earlier work [1] that such a machine actually can generate entanglement between two qubits, only by leveraging a temperature bias. While the entanglement was both weak and noisy, it motivated the following natural question: how strong entanglement is actually possible to produce with these thermodynamically minimalistic resources? In the years since, a series of works have step by step strengthened the entanglement – sometimes at the price of introducing some extra resources. Still, the best entanglement so far obtained is far from optimal.

In our work [2], we conclusively solve this problem. We propose a quantum thermal machine which only uses a chemical potential bias in order to generate a maximally entangled qubit pair, or in fact, any desired pure two-qubit entangled state, emerging as a dark state of the system. The key insight is the addition of an extra qubit which serves as an aid for generating the entanglement between other constituents of the machine. Crucially, we prove that this is the minimal thermal machine that can produce maximal entanglement. Going beyond bipartite entanglement, we generalise our thermal machine to produce genuinely multipartite entangled states of n qubits using an architecture of $2n - 1$ qubits. Remarkably, the architecture is able to produce W states of an arbitrary number of qubits using only local interactions and a chemical potential bias. Our results reveal the striking fundamental capabilities of quantum thermal machines at minimal control.

[1] New J. Phys. **17**, 113029 (2015)

[2] `arXiv:2401.01776` (2024)

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13. **Stanisław Kurdziałek** ⇑

University of Warsaw

Quantum Metrology Using Quantum Combs and Tensor Network Formalism

We develop an efficient algorithm for determining optimal adaptive quantum estimation protocols with arbitrary quantum control operations between subsequent uses of a probed channel. We introduce a tensor network representation of an estimation strategy, which drastically reduces the time and memory consumption of the algorithm, and allows us to analyze metrological protocols involving up to $N = 50$ qubit channel uses, whereas the state-of-the-art approaches are limited to $N < 5$. The method is applied to study the performance of the optimal adaptive metrological protocols in presence of various noise types, including correlated noise.

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14. **Joanna Majsak** ⇑

University of Warsaw

A Simple and Efficient Joint Measurement Strategy for Estimating Fermionic Observables and Hamiltonians

Measuring non-commuting observables is a non-trivial problem often encountered in quantum computing. We address it by proposing a simple scheme to estimate fermionic observables and Hamiltonians relevant in quantum chemistry and correlated fermionic systems. Our approach is based on implementing a measurement that jointly measures noisy versions of any product of two or four Majorana operators in an N-mode fermionic system.

To realize our measurement we use: (i) a randomization over a set of unitaries that realize products of Majorana fermion operators; (ii) a unitary, sampled at random from a constant-size set of suitably chosen fermionic Gaussian unitaries; (iii) a measurement of fermionic occupation numbers; (iv) suitable post-processing. Our scheme can estimate expectation values of all quadratic and quartic Majorana monomials to ϵ precision using $O(N \log(N)/\epsilon^2)$ and $O(N^2 \log(N)/\epsilon^2)$ measurement rounds respectively, matching the performance offered by fermionic shadow tomography. In certain settings, such as a rectangular lattice of qubits which encode an N-mode fermionic system via the Jordan-Wigner transformation, our scheme can be implemented in circuit depth $O(N^{1/2})$ with $O(N^{3/2})$ two-qubit gates, offering an improvement over fermionic and matchgate classical shadows that require depth $O(N)$ and $O(N^2)$ two-qubit gates. By benchmarking our method on exemplary molecular Hamiltonians and observing performances comparable to fermionic classical shadows, we demonstrate a novel, competitive alternative to existing strategies.

The talk is mainly based on [1]. The scheme is asymptotically optimal within the framework of joint measurability, as shown in [2], which studies theory of joint measurability of Majorana fermion operators from a more formal perspective, exploring its connections to graph and design theory, as well as topics in mathematical physics such as the SYK model.

[1] arXiv:2402.19230 (2024)

[2] arXiv:2402.19349 (2024)

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15. **Ignacio Perito** ⇑

ICFO

Randomness Certification on Qudit Systems

In the two parties, two settings and two outcomes Bell scenario, maximal violation of the CHSH inequality has the surprising property of self-testing the strategy used to attain this value. In other words, it certifies that a given pair of mutually unbiased measurements is being performed over each half of a maximally entangled state of two qubits. From there, it is not hard to devise a strategy to certify that two bits of genuine randomness can be extracted from this setup in a device independent manner. Moreover, with the aid of semidefinite programming, one can see that this result is robust, in the sense that some genuine randomness can still be certified in the presence of noise.

When the number of outcomes is more than two, Bell inequalities maximally violated by local mutually unbiased measurements exist but, except in the ternary outcome case, they lack the self-testing property. Besides that, they are inconvenient for robust randomness certification for other two reasons: first, they require as many measurement settings as possible outcomes, making the scaling of the numerical robustness proofs difficult and, second, the gap between the local bound and the quantum bound for these inequalities is small, which makes them highly susceptible to noise even when they certify the desired amount of randomness in the ideal case.

In this talk, we will explore different strategies for device independent certification of randomness in quantum systems beyond qubits using well known Bell inequalities in the two settings scenario, and we will also discuss our current efforts towards designing Bell inequalities tailored to certify a pair of mutually unbiased measurements in this scenario for dimensions higher than two.

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16. **Marco Radaelli** ⇑

Trinity College Dublin

Parameter Estimation for Quantum Jump Unraveling

We consider the estimation of parameters encoded in the measurement record of a continuously monitored quantum system in the jump unraveling. This unraveling picture corresponds to a single-shot scenario, where information is continuously gathered. Here, it is generally difficult to assess the precision of the estimation procedure via the Fisher Information due to intricate temporal correlations and memory effects. In this paper we provide a full set of solutions to this problem.

First, for multi-channel renewal processes we relate the Fisher Information to an underlying Markov chain and derive a easily computable expression for it. For non-renewal processes, we introduce a new algorithm that combines two methods: the monitoring operator method for metrology and the Gillespie algorithm which allows for efficient sampling of a stochastic form of the Fisher Information along individual quantum trajectories. We show that this stochastic Fisher Information satisfies useful properties related to estimation in the single-shot scenario.

Finally, we consider the case where some information is lost in data compression/post-selection, and provide tools for computing the Fisher Information in this case. All scenarios are illustrated with instructive examples from quantum optics and condensed matter.

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17. Grzegorz Rajchel-Mieldzioć ⇑

ICFO

Entanglement Classification and Non-k-Separability Certification via GHZ-Class Fidelity

Many-body quantum systems can be characterised using the notions of k-separability and entanglement depth. A quantum state is k-separable if it can be expressed as a mixture of k entangled subsystems, and its entanglement depth is given by the size of the largest entangled subsystem.

In this paper we propose a multipartite entanglement measure that satisfies the following criteria: (i) it can be used with both pure and mixed states; (ii) it is encoded in a single element of the density matrix, so it does not require knowledge of the full spectrum of the density matrix; (iii) it can be applied to large systems; and (iv) it can be experimentally verified.

The proposed method allows the certification of *non*-k-separability of a given quantum state. We show that the proposed method successfully classifies three-qubit systems into known stochastic local operations and classical communication (SLOCC) classes, namely bipartite, W-, and GHZ-type entanglement. Furthermore, we characterise the *non*-k-separability in known nine SLOCC classes of four-qubit states, absolutely maximally entangled states for five and six qubits and for arbitrary size qubit Dicke states.

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18. **Jordi Romero i Pallejà** ⇑

Universitat Autònoma de Barcelona

PPT-Bound Entanglement as a Pseudo-Convex Combination of Separable States

Our work focuses on the separability problem; i.e., determining whether a given state is entangled or not. This problem has attracted significant attention from physicists worldwide, not only due to its intrinsic mathematical elegance but also because of its critical implications for potential quantum technologies.

The separability problem is an extremely challenging problem which is known to be NP-Hard. There exist some criteria that allow us to partially solve the problem in the bipartite case for generic states. One of those, and probably the most powerful one, is the Peres-Horodecki or PPT criterion, which states that the partial transposition of any separable state is another state; i.e., the partial transposition of a separable state is semidefinite positive. The PPT criterion tells us that any state which is NPT; i.e., its partial transposition is not semidefinite positive, is necessarily entangled. One of the main reasons why this criterion is of paramount importance when tackling the separability problem is that it is, operationally speaking, extremely easy to implement. Nonetheless, this criterion is both necessary and sufficient only for bipartite states of global dimension smaller or equal to 6 (two qubits or a qubit and a qutrit). This means that, for bipartite states with dimension 7 or greater, there do exist entangled states that cannot be detected with this criterion.

In this work, we focus on the first bipartite physical system with global dimension greater than 6; i.e., the first systems where there exists PPT-Entanglement (PPT criterion is necessary but not sufficient anymore). We present a novel approach, which we have dubbed as pseudo-convex combination, which allows us to give a constructive analytical procedure to find PPT-Entangled states from separable states and allows us to completely solve the separability problem for bipartite symmetric states of qutrits.

Moreover, the powerfulness of the pseudo-convex combination we present resides in the fact that, even though we employ it for bipartite symmetric states of qutrits, it can still be used as a constructive algorithm to find PPT-Entangled states in generic bipartite states outside the symmetric subspace, where the problem is known to be NP-Hard.

The implications of our research are profound, offering new insights and practical tools for advancing quantum information theory. In summary, our work presents a novel approach to the separability problem, utilizing the pseudo-convex combination method to constructively identify PPT-Entangled states, which allows to fully solve the separability problem for bipartite symmetric states of qutrits.

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19. Shubhayan Sarkar ⇑

Université Libre de Bruxelles

Quantum Steering Without Inputs

Quantum networks with independent sources allow the observation of quantum nonlocality without inputs. Consequently, the incompatibility of measurements is not a necessity for observing quantum nonlocality when one has access to independent sources. Here we investigate the minimal scenario without inputs where one can observe any form of quantum nonlocality.

We show that even two parties with two sources that might be classically correlated can witness a form of quantum nonlocality, in particular quantum steering, in networks without inputs if one of the parties is trusted, that is, performs a fixed known measurement. We term this effect as swap-steering. The scenario presented in this work is minimal to observe such an effect. Consequently, a scenario exists where one can observe quantum steering but not Bell non-locality.

We further construct a linear witness to observe swap-steering. Interestingly, this witness enables self-testing of the quantum states generated by the sources and the local measurement of the untrusted party. This in turn allows certifying two bits of randomness that can be obtained from the measurement outcomes of the untrusted device without the requirement of initially feeding the device with randomness. Furthermore, we find linear witnesses corresponding to any negative partial transpose (NPT) bipartite state and any bipartite state that violates the computable cross-norm (CCN) criterion.

Moreover, by considering that the trusted party can perform tomography of the incoming subsystems, we construct linear inequalities to witness swap-steerability of every bipartite entangled state. Consequently, for every bipartite entangled state one can now observe a form of quantum nonlocality.

[1] arXiv:2307.08797 (2023)

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20. **Razin Shaikh** ⇑

University of Oxford

The Focked-up ZX Calculus: Picturing Continuous-Variable Quantum Computation

While the ZX and ZW calculi have been effective as graphical reasoning tools for finite-dimensional quantum computation, the possibilities for continuous-variable quantum computation (CVQC) in infinite-dimensional Hilbert space are only beginning to be explored. In this work, we formulate a graphical language for CVQC. Each diagram is an undirected graph made of two types of spiders: the Z spider from the ZX calculus defined on the reals, and the newly introduced Fock spider defined on the natural numbers. The Z and X spiders represent functions in position and momentum space respectively, while the Fock spider represents functions in the discrete Fock basis. In addition to the Fourier transform between Z and X, and the Hermite transform between Z and Fock, we present exciting new graphical rules capturing heftier CVQC interactions.

We describe the diagrammatic representation of the universal set of gates for CVQC, which consists of Gaussian and non-Gaussian operations. Moreover, we prove that our calculus is complete for the Gaussian fragment of CVQC; i.e., for any two Gaussian diagrams representing the same linear map, there exists a proof of their equality within the graphical calculus.

Applying our calculus for quantum error correction, we derive graphical representations of the Gottesman-Kitaev-Preskill (GKP) code encoder, syndrome measurement, and magic state distillation of Hadamard eigenstates. Finally, we elucidate Gaussian boson sampling – a non-universal quantum computation problem believed impossible to simulate classically – by providing a fully graphical proof that its circuit samples submatrix hafnians.

[1] arXiv:2406.02905 (2024)

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21. **Armin Tavakoli** ⇑

Lund University

Imprecise Measurements in Quantum Correlations

Many quantum information schemes assume that experiments can precisely implement theoretically stipulated measurements. I discuss the consequences of measurements featuring tiny imprecision. This is considered first in the context of entanglement witnessing and then in the context of quantum steering. The first key finding is that small errors can have large impact, thereby leading to significant false positives, compromises of protocols' security and over-estimation of the quantum resources under consideration.

Consequently, I discuss methods for properly taking the lack of perfect measurement control into account, in both entanglement and steering experiments. For steering, this also turns out to lead to an interesting phenomenon: suitable steering tests can take measurement imperfections into account without any incurring cost to the detection power.

[1] Phys. Rev. Lett. **128**, 250501 (2022)

[2] Phys. Rev. Lett. **132**, 070204 (2024)

22. **Guilherme Zambon** ⇑

University of Nottingham

Process Tensor Distinguishability Measures

Process tensors are quantum combs describing the evolution of open systems through multiple steps of general quantum dynamics. While there is more than one way to measure how different two processes are, special care must be taken to ensure quantifiers obey physically desirable conditions such as data processing inequalities.

Here, we analyze two classes of distinguishability measures commonly used in general applications of quantum combs. We show that the first class, called Choi divergences, does not satisfy an important data processing inequality, while the second one, which we call generalized divergences, does. We also extend to quantum combs some other relevant results of generalized divergences of quantum channels. Finally, given the properties we proved, we argue that generalized divergences may be more adequate than Choi divergences for distinguishing quantum combs in most of its applications. Particularly, this is crucial for defining monotones for resource theories whose states have a comb structure, such as resource theories of quantum processes and resource theories of quantum strategies.

Posters

1. **Bihalan Bhattacharya** ⇑

Nicolaus Copernicus University

Schwarz Qubit Maps with Diagonal Unitary and Orthogonal Symmetries

We have analyzed a class of unital qubit maps with diagonal unitary and orthogonal symmetries. Complete characterization of this class of maps showing the intricate relation between positivity, operator Schwarz inequality, and complete positivity have been provided. The first example of Schwarz but not completely positive map found by Choi belongs to our class. We have generalized the picture to non unital case (so called generalized Schwarz maps).

As a case study we provide a full characterization of Pauli maps which leads to generalization of seminal Fujiwara-Algoet conditions for Pauli quantum channels.

[1] arXiv:2404.10895 (2024)

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2. **Conall Campbell** ⇑

Queen's University Belfast

Characterisation of Quantum Network Topologies through Genetic Optimisation of Sink Measurements

Knowing the topology of quantum networks provides valuable insights into the behaviour of the network, its capabilities, and its potential use for various quantum information processing tasks.

Currently, there is major interest in the transfer of photonic excitations in macromolecules (photosynthesis), where a photon is absorbed and travels through a molecule to a reaction centre, where it is then transformed into sustenance for the plant. This process can be modelled through continuous-time quantum walks, where the spread within the network of an initially localised excitation is monitored as a function of time. However, physically, we may not always know the exact configuration of a network's topology due to the complexity of macromolecules.

We attach a sink at one node to probe our network which results in an irreversible decay process that traps the excitation in the sink. By monitoring the sink population at different moments in time for all nodes, we can infer the network's topology.

We feed the sink population data into a machine-learning protocol, i.e., a genetic algorithm which is trained to consider any quantum network and determine its topology. This is accomplished through comparing the measurements of the sink to that of a target network with the same output data. The algorithm will then be trained to consider a limited number of sink measurements, akin to a physical experimental setup involving macromolecules, and test its performance when the excitation traversing the network is exposed to noise

This approach relies on probes, making it less experimentally demanding and more advantageous over current approaches which require one to monitor the population at each node in the network. Furthermore, our approach would also limit the required amount of post-processing.

This work is crucial to quantum networking because we can provide a deeper understanding of efficient energy transfer in biologically inspired quantum networks. These biological networks are known to mitigate dephasing effects whilst also maintaining quantum coherence. Therefore, this work is paramount to the advancement of quantum networking and quantum-based technologies.

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3. **Kai-Siang Chen** ⇑

National Cheng Kung University

Bounding the Minimal Average Communication Cost of Nonlocal Correlations

In the study of device-independent quantum information, Bell nonlocality plays a fundamental role in excluding the local hidden variable (LHV) models from replicating the input-outcome statistic between parties from quantum mechanics. However, this conclusion is established under the premise that no communications between the parties are allowed. In other words, LHV models augmented with classical communications may reproduce, nonlocal quantum correlations, which suggests that the minimal average communication cost (MACC) for simulating a correlation is an appropriate measure of nonlocality. Even though being an intuitive measure of nonlocality, the computational resources required to evaluate MACC increases rapidly with the number of inputs and outcomes, thus making MACC difficult to determine in practice.

In this work, we introduce computationally feasible methods to lower bound MACC for 2-partite Bell scenarios. Additionally, we explore the relationship between nonlocality robustness (NR) and MACC and provide conjectured upper bound and lower bound of MACC based on NR. We provide the largest MACC lower bounds for quantum correlations found using these tools in several Bell scenarios.

4. **Sambunath Das** ⇑

Czech Academy of Sciences

Probing a Strongly Correlated System via Qubit Dynamics

Using a mobile qubit as a probe to study the properties of a larger quantum system is a novel technique that takes advantage of quantum properties of the probe, the system under study, and the interaction between them. This allows to obtain accurate information about the physical characteristics of a system of interest and often allows to determine system properties which are impossible or hard to study by classical measurement schemes. The idea relies on treating the system as an environment from the perspective of the qubit and measure qubit decay or decoherence. Such an indirect measurement is advantageous because the qubit is easily accessible experimentally while its position and the properties of the qubit and interaction can be tuned to a high extent. In this context, the extension of the method to the study of strongly correlated systems, which display complex properties and are a challenge to measure, is of great importance.

In this talk, I will present our recent work on using a qubit probe to investigate the properties of an anisotropic Heisenberg XXZ spin-$\frac{1}{2}$ chain, an archetypical example of a strongly correlated system. I will describe the methodology, which integrates techniques from open quantum system theory, specifically the Time-Convolutionless (TCL) projection operator method, with those from the study of strongly correlated systems, particularly the Time-Dependent Variational Principle (TDVP) method. The TDVP method provides a reliable evolution of the qubit, while the TCL method helps interpret this evolution in terms of the spin chain's properties.

I will conclude by discussing how the behavior of the TCL and TDVP curves of the qubit coherence indicator can be used to characterize the critical quantum phase transition points. This combined approach offers a powerful tool for probing and understanding the intricate properties of strongly correlated systems.

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5. **Marco Fellous-Asiani** ⇑

University of Warsaw

In Concatenated Quantum Computing, Magic States are Often the Last Resource to Optimize

Fault-tolerant quantum computers usually have easy and hard gate operations; the hard gate-operations require the preparation, verification and injection of complicated states called magic states, while easy gate-operations (often implemented transversally) do not. Many expect that a computation's physical resource requirements (qubits, gates, etc.) are dominated by the magic states, making it crucial to minimize them. However, we show this expectation is often incorrect for concatenated error-correction schemes.

To demonstrate this, we develop a general scaling approach that gives simple closed-form expressions for resources, even for multiple levels of concatenation. As examples, we apply this to 7-qubit code with two types of error-correction (i) Steane error-correction gadget, and (ii) flag-qubit error-correction gadget. In realistic situations, we show that specific optimizations, involving sharing ancillas or using smaller errror-correction gadgets, can reduce resource costs by orders of magnitude. In contrast, optimizing magic states only reduces resource costs by a modest amount, particularly if the other optimizations are not performed first.

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6. **Srijon Ghosh** ⇑

University of Warsaw

Operational Ergotropy: Suboptimality of the Geodesic Drive

Ergotropy is the most elegant thermodynamic way to access individual quantum systems, resulting from the miniaturization of thermal machines to certify quantum correlations. However, in the traditional framework of ergotropy, the explicit role of time and its optimality in extracting the work has yet to be explored. Here, we put forth a notion of optimality for extracting ergotropic work, derived from an energy constraint governing the necessary dynamics for work extraction in a quantum system. Within the traditional ergotropy framework, which predicts an infinite set of equivalent pacifying unitaries, we demonstrate that the optimal choice lies in driving along the geodesic connecting a given state to its corresponding passive state.

Moreover, in a practical scenario where unitaries are inevitably affected by environmental factors, we refine the definition of ergotropy and introduce the notion of operational ergotropy. It enables the characterization of work extraction in noisy scenarios. We find that for certain typical noise models, the optimal choice that governs the Schrödinger part of the dynamics aligns with the optimal drive in the unperturbed scenario. However, we demonstrate that such optimality is not universal by presenting an explicit counterexample. Additionally, within this generalized framework, we discuss the potential for faster work extraction from quantum systems in the presence of noise.

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7. Saronath Halder

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Center for Theoretical Physics PAS

Unambiguously Locally Unidentifiable Mixed States and Input State Independent Entanglement Generation

We consider a set of orthogonal mixed states such that the sum of the ranks of these states is equal to the total dimension of the considered Hilbert space. Here the number of parties is greater than or equal to two. However, we study the necessary and sufficient condition for which no state from the aforesaid set can be unambiguously identified under local operations and classical communication.

We also show that this problem has connection with the following problem. We want to design a projective measurement other than rank one measurement. This should be done in such a way that when we apply such a measurement on any product state, it always outputs an entangled state, does not matter what is the form of the input product state.

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8. **Majid Hassani** ⇑

Leiden University

Privacy in the Network of Quantum Sensors

We address privacy in a network of quantum sensors where only trusted parties are permitted to access the result and achieves optimal precision. We introduce a quantitative definition of privacy and derive the optimal state achieving maximum privacy. We also introduce the notion of quasi-privacy (ϵ-privacy) and discuss the effect of uncorrelated noise on the privacy of the network.

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9. **Arturo Konderak** ⇑

Center for Theoretical Physics PAS

Asymptotic Dynamics of Open Quantum Systems

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10. **Mu-En Liu** ⇑

National Cheng Kung University

Entanglement Transitivity from $(\lceil N/2\rceil + 1)$-Body Marginals of an N-Body Pure State May Be Generic

Generally, the marginals of a quantum state do not single out a compatible global state. There are, however, exceptions in a many-body situation. It is known [1] that any two bipartite marginals obtained from a generic tripartite pure state uniquely determine the global state if the overlapping marginal has a dimension larger than or equal to the others. Furthermore, it is known [2] that, generically, all two-qudit marginals of such tripartite pure states are entangled. Together, the two results entail that the two two-qudit marginals of any generically sampled three-qudit pure states must also force the remaining two-qudit marginal to be entangled, i.e., such bipartite marginal states exhibit generic transitivity of entanglement, confirming the conjecture posted by some of the present authors [3].

Additionally, we provide evidence showing that the k-body marginals originating from a generic N-body pure state for $k \geqslant (\lceil N/2\rceil + 1)$ are generically entangled. In particular, $\lfloor N/2\rfloor$ of these k-body marginals not only uniquely determine the underlying N-body global state, but also exhibit entanglement transitivity.

[1] Phys. Rev. A **88**, 012109 (2013).

[2] J. Phys. A: Math. Theor. **41**, 375305 (2008).

[3] npj Quant. Inf. **8**, 98 (2022).

11. **Paolo Luppi** ⇑

University of Milan

Multi-time Statistics and Non-Markovianity in Open Quantum Systems

Multi-time statistics in quantum systems are crucial for both fundamental research, such as studying the Leggett-Garg inequalities (the "temporal Bell's inequality"), and practical applications, like quantum information protocols. When examining multi-time correlation functions in open quantum systems, intriguing effects can emerge, especially under Non-Markovian dynamics.

In this poster, we analyze multi-time statistics for open quantum systems by investigating the connection between the quantum regression theorem and non-Markovianity. The quantum regression theorem is a powerful tool for calculating multi-time correlation functions and it is valid in the context of Markovian multi-time statistics. However, there is not a clear correspondence between non-Markovianity in multi-time statistics and non-Markovianity in the dynamics.

To provide a comprehensive understanding, our approach includes a microscopic derivation in the weak coupling regime as well as non-perturbative methods, such as the pseudo-mode technique. This technique involves simulating an open quantum system by exploiting a general equivalence between the reduced dynamics of an open quantum system interacting unitarily with a bosonic environment and the dynamics of the same system interacting with a typically less complex harmonic environment subjected to a Lindblad evolution.

12. **Piotr Masajada** ⇑

Institute of Fundamental Technological Research PAS

Numerical Computation of the Geometric Entanglement in Multipartite Systems.

Quantifying the amount of entanglement in a given quantum state is a difficult problem. In recent years, several entanglement quantifiers have been developed, each having its pros and cons. One of the most useful of them is the geometric entanglement. Unfortunately, computing the value of such a quantifier is a computationally demanding task.

In our poster, we present a method of computing the geometric entanglement for mixed multipartite systems that uses semi-definite programming. Semi-definite programming is an efficient method of performing numerical optimization tasks. We will show that in some not-too-high dimensional cases, this method can be used to efficiently compute the amount of entanglement in a given quantum state. Additionally, we show that our method quantifies entanglement even in bound entangled states. We also describe bound entanglement in Heisenberg spin chains.

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13. Hannah McAleese ⇑

Queen's University Belfast

Analysing Information Back-Flow in Measurement-Free Teleportation

Quantum teleportation demonstrates entanglement's power as a resource: jointly measuring the quantum states of two particles enables the sending of a quantum state to another particle without a quantum channel.

While typically associated with long-distance quantum communication, its relevance to quantum computation is significant. The measurement-free teleportation protocol, known as the BBC protocol [1], was specifically designed for this purpose. Rather than introducing non-Markovianity through an external environment, we analyse its potential inherent presence in the protocol. Despite previous studies linking non-Markovianity to teleportation [2], this analysis aims to explore the dynamics and correlations within the protocol itself, revealing surprising challenges in connecting the two.

[1] Physics D **120**, 43 (1998)

[2] `arXiv:2203.00668` (2022)

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14. **Moein Naseri** ⇑

Institute of Fundamental Technological Research PAS

Quantum Speed Limits for Change of Basis

Quantum speed limits provide ultimate bounds on the time required to transform one quantum state into another. Here, we introduce a novel notion of quantum speed limits for collections of quantum states, investigating the time for converting a basis of states into an unbiased one as well as basis permutation. Establishing an unbiased basis, we provide tight bounds for the systems of dimension smaller than 5, and general bounds for multi-qubit systems and the Hilbert space dimension d. For two-qubit systems, we show that the fastest transformation implements two Hadamards and a swap of the qubits simultaneously.

We further prove that for qutrit systems the evolution time depends on the particular type of the unbiased basis. Permuting a basis, we obtain the exact expression for the Hilbert space of dimension d. We also investigate speed limits for coherence generation, providing the minimal time to establish a certain amount of coherence with a unitary evolution.

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15. **Lubashan Pathirana** ⇑

University of Copenhagen

Asymptotic Purification of Quantum Trajectories in a Stationary Random Environment

In the absence of dark subspaces, asymptotic purification of a quantum trajectory independent of the initial state under repeated indirect measurements was first established by Kümmerer and Maassen in 2006.

In the current work, we generalize these results to the setting where each measurement is not necessarily independent of the previous one but is performed through a sequence of stationary and ergodic measurements. We introduce the notion of a random dark subspace, a measurable multi-valued function, and upon its almost sure absence, we are able to prove the asymptotic purification of quantum trajectories under time-dependent generalized measurements.

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16. **Matthias Salzger** ⇑

ICTQT, University of Gdańsk

A Decompositional Framework for Process Theories in Spacetime

There has been a recent surge in interest in quantum foundations coming from incorporating ideas from general relativity and quantum gravity. In particular, the field of indefinite causal order has emerged and is now an important research topic in its own right. Many of the tools that we use in quantum foundations and information, are, however, totally agnostic as to the underlying spacetime in which the quantum systems live. To give a practical example, whenever we draw a quantum circuit we are not taking into account the connectivity of the physical qubits which will realize this circuit.

In this work, we aim to address this limitation. In particular, we show how to extend the formalism of process theories (a framework to study both quantum and post-quantum theories) to incorporate a background causal structure arising from a fixed spacetime. We discuss when processes are embeddable in spacetime under certain constraints. To this end, we introduce the concept of implementations of a process, which are decompositions of the process. A process is then embeddable if one of its implementations can be embedded in such a way that all the processes are localized and all wires follow time-like paths. The set of all implementations of a process is a rather unwieldy object but we show that there exists a subset with useful properties which tells us everything we need to know about the remaining implementations and the embeddability of a process. We call this subset minimal representatives.

Future directions include plans to define and analyse the compositional structure of the framework more rigorously, extending the framework to indefinite causal structures, studying exotic causal influence and using the minimal representatives to probe the decompositional structure of quantum theory and beyond.

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17. **Amrapali Sen** ⇑

ICTQT, University of Gdańsk

An Operational Analysis of Superluminal Observers

The theory of relativity is generally assumed to provide us with a speed limit for all interactions. Nevertheless, over the years, this assumption has been frequently questioned and the idea of breaking this speed limit has popped up from time to time in an attempt to explain various phenomena. Most recently, Ekert and Dragan have argued that in a world with superluminal observers local determinism is impossible. In this way, the inherent randomness of quantum theory could be not just reconciled with the theory of relativity but the former can be understood as a consequence of the latter. The aim of our work is to develop an operational framework that allows for superluminal observers in a theory independent way.

We analyze several scenarios which hint at the fact that superluminal observers and superluminal Lorentz transformations are inconsistent with fundamental physical principles and experimental procedures known to be possible in the real world regardless of the underlying theory. This also sheds new insights into why we possibly should not observe superluminal observers as the connection between relativity and quantum theory.

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18. **Małgorzata Strzałka** ⇑

Czech Academy of Sciences

Qubit-Environment Entanglement in Time-Dependent Pure Dephasing for Transmon Qubits

Qubit-environment entanglement in time-dependent pure dephasing for transmon qubits We generalized the methods for quantification of system-environment entanglement that were previously developed for interactions that lead to pure decoherence (PD) of the system for time-independent Hamiltonians to time-dependent Hamiltonians. We have shown that the if-and-only-if criteria of separability [1], the entanglement measure [2], and the methods of detecting entanglement through operations and measurements performed only on the system without access to the environment [3] generalize in a straightforward manner to the case of time-dependent Hamiltonians. Thus the theoretical study of this type of entanglement is straightforward, while the time-dependence can enable experimental detection of entanglement for a wider class of PD interactions.

The methods were used to study the evolution of system-environment entanglement of a transmon qubit interacting with microwave cavity photons [4] for an interaction switching between an entangling and a non-entangling one. This allows us to study nontrivial dependencies between the buildup of classical and quantum correlations, as the buildup of entanglement does not directly follow the switching of the interaction [5]. Furthermore, we show how to detect entanglement in this system, which is undetectable by the time-independent methods due to symmetries in the Hamiltonian, by taking advantage of the controllable time-dependence of the interaction.

[1] Phys. Rev. A **92**, 032310 (2015)

[2] Phys. Rev. Research **2**, 043062 (2020)

[3] Phys. Rev. A **104**, 042411 (2021)

[4] Nature **584**, 368 (2020)

[5] Phys. Rev. A **109**, 032412 (2024)

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19. Nidhin Sudarsanan Ragini ⇑

Slovak Academy of Sciences

Labeling Outcomes of Quantum Measurement Devices

It is not everyday one finds themselves with a quantum measurement device and being oblivious regarding the quantum theoretic descriptions associated with each of the outcome labels. When that day comes, we ask the question whether, and for which quantum observables, we can identify these lost associations through finite implementations of these "unlabeled" devices. In this talk, we sketch these tasks, referred to as "quantum labeling tasks", and investigations carried out on them. Apparently, we find that these tasks are equivalent to a restricted class of quantum observable distinguishability tasks.

As such, we look at this problem in the single and multiple-shot regimes and discover what classes of observables fare well enough to be labeled, as permitted by quantum theory.

Moreover, we also discover an operational distance between effects (POVM elements) as a measure of "observable labelability".

[1] Phys. Rev. A **109**, 052415 (2024)

[2] arXiv:2407.05392 (2024)

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20. **Matthew Sutcliffe** ⇑

University of Oxford

Fast Classical Simulation of Quantum Circuits via Parametric Rewriting in the ZX-Calculus

The ZX-calculus is an algebraic formalism that allows quantum computations to be simplified via a small number of simple graphical rewrite rules. Recently, it was shown that, when combined with a family of "sum-over-Cliffords" techniques, the ZX-calculus provides a powerful tool for classical simulation of quantum circuits. However, for several important classical simulation tasks, such as computing the probabilities associated with many measurement outcomes of a single quantum circuit, this technique results in reductions over many very similar diagrams, where much of the same computational work is repeated.

In this paper, we show that the majority of this work can be shared across branches, by developing reduction strategies that can be run parametrically on diagrams with boolean free parameters. As parameters only need to be fixed after the bulk of the simplification work is already done, we show that it is possible to perform the final stage of classical simulation quickly utilising a high degree of GPU parallelism. Using these methods, we demonstrate speedups upwards of 100× for certain classical simulation tasks vs. the non-parametric approach.

[1] arXiv:2403.06777 (2024)

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21. **Eloïc Vallée** ⇑

Leiden University

Geometrical Aspects of the TINN Polytope from Graph Theory

Bell nonlocality is a fundamental concept in quantum mechanics, demonstrating that spatially separated particles can exhibit correlations that cannot be explained by classical physics. To distinguish between nonlocal and local correlations, we use the so-called Bell inequalities, which collectively form a polytope known as the local set. While it is feasible to fully characterize the local set for a small number of parties, the task becomes exponentially complex as the number of parties increases.

In this study, we tackle the challenge of characterizing the local polytope for a large number of parties by focusing on a specific projection of the polytope: the translation-invariant nearest neighbor (TINN) projection. We show that there exists a deep connection between graph theory and TINN Bell inequalities, enabling us to establish that the TINN local polytope has a finite number of vertices, regardless of the number of parties involved. This allows us to explore Bell inequalities in large 1D systems with translational symmetry.

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22. **Rafael Wagner** ⇑

International Iberian Nanotechnology Laboratory

Unitary-Invariant Witnesses of Quantum Imaginarity.

Hickey and Gour introduced a quantum resource theory based on the fact that, for a given fixed basis of reference some states have coherences necessarily described by complex numbers. They termed this the "imaginarity" of a quantum state. In spite of this rigorous resource-theoretic treatment, its usefulness was initially unclear. Some early results in the literature suggested that imaginarity had no relevant role, as, for instance, various real-only formulations of quantum mechanics were known.

Moreover, quantum theory restricted to real amplitudes was shown to be universal for quantum computation, and capable of reproducing the statistics of any Bell experiment. Any generic complex-valued quantum computation can be evaluated using only real amplitudes by using an extra auxiliary qubit. In such a way, free states and observables defined in the larger system reproduce all predictions of the resourceful states and observables since both Born rule statistics return equal values.

In this talk I will present recent work where we develop the theory characterizing the role of these invariants as witnesses of quantum imaginarity. They are experimentally promising, and their usage shares many of the benefits of using the Bell nonlocal network approach of Renou et. al. – independence of basis and dimension, with no need for further assumptions such as local tomography. Our tests are not device-independent, and assume the statistics to correspond to values of unitary-invariants, measurable in relatively straightforward experiments which we briefly describe.

We start with the foundational question of what complex values 3-state invariants can assume, and solve this problem completely by characterizing the region in the complex plane where all possible third-order invariants must lie. For this scenario with 3 pure states, we prove that pairwise overlaps cannot witness imaginarity. This is because any pairwise overlap triple, arising out of arbitrary triples of quantum states, can be alternatively obtained from states whose amplitudes are real-valued.

Besides the complete characterization of which values 3-state invariants can take, we obtain a partial characterization of the 4-state scenario. We show that, unlike the 3-state case, the imaginarity of 4 states can be witnessed with pairwise overlap measurements only. This allows for simplified experimental tests to witness imaginarity of four states, as pairwise overlaps are simpler to measure than higher-order Bargmann invariants.

We also briefly discuss implications of our results for the quantitative description of weak values, Kirkwood-Dirac quasiprobability distributions, multiphoton indistinguishability, and geometric phases.

[1] arXiv:2403.15066 (2024)
