**Higgs Centre Workshop: Entanglement, Information and Complexity in Quantum Systems**

**6-8 May 2025, University of Edinburgh**

**Abstracts**

**Invited Speakers**

**Chris Akers** (University of Colorado Boulder) - Finding quantum gravity answers to our questions in 1+1d

We would like a theory of quantum gravity so that we can answer pesky questions, like “what really happens if I dive into a generic black hole?” However, we now have a solvable theory of quantum gravity in 1+1d, and we \*still\* are having trouble because it’s tricky to even formulate the questions properly. In this talk I will (1) explain why this is tricky, and (2) propose how we should be doing this systematically, arriving at concrete answers in this low dimensional gravity theory.

**Zvika Brakerski** (The Weizmann Institute, Israel) - Quantum Cryptography and Computational Entanglement Theory

In this talk I will survey some of the developments in the foundations of quantum cryptography in recent years. I will then focus on the notion of pseudo-entanglement that has received attention recently. More broadly, I will discuss the recent effort to come up with a "computational entanglement theory" that introduces computational limitations into the study of entanglement.

**Jens Eisert** (Freie Universität Berlin) - Entanglement, information and complexity in quantum systems: An operational perspective

In this talk, held in the morning after the conference dinner, we will revisit the core questions of the conference from an operational perspective. We will ask in what precise way entanglement and complexity are connected to each other [1–3]. We will show that the average-case time evolution of interacting quantum systems can, in a precise way to be explained, be surprisingly uncomplex—despite the fact that time evolution under local Hamiltonians is BQP-complete [4]. Building on this, we will demonstrate that entanglement theory is turned upside down if one accepts that all implemented operations must be both computationally and sample efficient [5]. Taking the idea of an operational perspective to a new level, we will show that there are systems that are not quantum chaotic (and hence not "complex"), even though no polynomially bounded observer can distinguish them from Gaussian unitary ensembles, which paradigmatically represent quantum chaotic systems [6]. We will conclude the talk by discussing the role of the observer — who collects data and acts operationally efficiently — in shaping the notions of entanglement, information, and complexity.

[1] Nature Physics 18, 528 (2022).
[2] Physical Review Letters 127, 020501 (2021).
[3] PRX Quantum 6, 010346 (2025).
[4] Nature Physics 20, 1401 (2024).
[5] arXiv:2502.12284 (2025).
[6] arXiv:2410.18196 (2024).

**Philippe Faist** (Freie Universität Berlin) -  Resource-theoretic approaches for complex many-body systems

I will present techniques based on the resource theory of thermodynamics and quantum information theory to quantify operational physical properties of many-body systems. In particular, I will discuss how the resource-theoretic picture can accommodate the concept of complexity. Quantum circuit complexity measures the difficulty of realizing a quantum process, such as preparing a state or implementing a unitary. I will consider the prototypical task of information erasure, or Landauer erasure, where an n-qubit memory is reset to the all-zero state. In this setting, I'll show that the trade-off between the thermodynamic work and computational complexity required for erasure is quantified by the complexity entropy, an entropy measure that quantifies the entropy a system appears to have to an observer of limited computational power. I'll discuss some information-theoretic aspects and properties of the complexity entropy. I'll show that in random circuits, the complexity entropy undergoes a transition from its minimal value to its maximal value at the point where the state reaches the maximal complexity that can still be resolved by the observer. I'll discuss implications for how to formulate the laws of thermodynamics in a way that a process is forbidden not only whenever it violates energetic or entropic conditions, but also when it is too complex to happen on a realistic time scale. Finally, I'll discuss some connections with maximum-entropy methods for quantum states and quantum channels.

**Alioscia Hamma** (University of Naples Federico II) - Why is magic important in holography

In recent years, the notion of magic in quantum physics - originally confined to more esoteric quantum information processing subfields - has attracted the attention of the community of quantum many-body physics, quantum chaos and complexity, high-energy physics, AdS-CFT and the foundations of quantum mechanics. In this talk, I will show why and how quantum magic matters to holography, how it describes gravitational back-reaction, and set up a program of entanglement-magic duality.

**Antonio Anna Mele** (Freie Universität Berlin) -Effect of noise in typical quantum circuits

Motivated by realistic hardware considerations of the pre-fault-tolerant era, we comprehensively study the impact of uncorrected noise on typical quantum circuits. We first show that any noise `truncates’ most quantum circuits to effectively logarithmic depth, in the task of estimating observable expectation values. We then prove that quantum circuits under any non-unital noise exhibit lack of barren plateaus for cost functions composed of local observables. But, we also design an efficient classical algorithm to estimate observable expectation values of typical quantum circuits within any target accuracy, in any circuit architecture. The runtime of the algorithm is independent of circuit depth, and it based on Pauli-path truncation methods. Taken together, our results showcase that, unless we carefully engineer the circuits to take advantage of the noise, it is unlikely that noisy quantum circuits provide any quantum advantage for algorithms that output observable expectation value estimates, like many variational quantum machine learning proposals.

(Talk based on [https://arxiv.org/abs/2403.13927](https://eur02.safelinks.protection.outlook.com/?url=https%3A%2F%2Farxiv.org%2Fabs%2F2403.13927&data=05%7C02%7C%7Ced46f07591c040f993fe08dd7c780884%7C2e9f06b016694589878910a06934dc61%7C0%7C0%7C638803577171415878%7CUnknown%7CTWFpbGZsb3d8eyJFbXB0eU1hcGkiOnRydWUsIlYiOiIwLjAuMDAwMCIsIlAiOiJXaW4zMiIsIkFOIjoiTWFpbCIsIldUIjoyfQ%3D%3D%7C0%7C%7C%7C&sdata=5QPUJ7i4Dwli97zX%2B0MrPRLBfhzV5JMEXfeauCRiXaE%3D&reserved=0), [https://arxiv.org/abs/2501.13101](https://eur02.safelinks.protection.outlook.com/?url=https%3A%2F%2Farxiv.org%2Fabs%2F2501.13101&data=05%7C02%7C%7Ced46f07591c040f993fe08dd7c780884%7C2e9f06b016694589878910a06934dc61%7C0%7C0%7C638803577171440489%7CUnknown%7CTWFpbGZsb3d8eyJFbXB0eU1hcGkiOnRydWUsIlYiOiIwLjAuMDAwMCIsIlAiOiJXaW4zMiIsIkFOIjoiTWFpbCIsIldUIjoyfQ%3D%3D%7C0%7C%7C%7C&sdata=Nrm2hCjJC5257d%2B8ga2jLfMEny8IlcAiAM0H%2FJrSyv8%3D&reserved=0))

**Zlatko Papic** (University of Leeds) - Disorder-tunable entanglement at infinite temperature

Emerging quantum technologies hold the promise of unraveling difficult problems ranging from condensed matter to high energy physics, while at the same time motivating the search for unprecedented phenomena in their setting. Here we utilise a custom-built superconducting qubit ladder to realise non-thermalising states with rich entanglement structures in the middle of the energy spectrum. Despite effectively forming an "infinite" temperature ensemble, these states robustly encode quantum information far from equilibrium, as we demonstrate by measuring the fidelity and entanglement entropy in the quench dynamics of the ladder. Our approach harnesses the recently proposed type of non-ergodic behaviour known as "rainbow scar", which allows us to obtain analytically exact eigenfunctions whose ergodicity-breaking properties can be conveniently controlled by randomising the couplings of the model, without affecting their energy. The on-demand tunability of quantum correlations via disorder allows for in situ control over ergodicity breaking and it provides a knob for designing exotic many-body states that defy thermalisation.

**Pablo Poggi** (University of Strathclyde) - Entanglement generation and collective behaviour in spin models with sparse coupling graphs

Quantum states featuring extensive multipartite entanglement are a resource for quantum-enhanced metrology, with sensitivity up to the Heisenberg limit. However, robust generation of these states using unitary dynamics typically requires all-to-all interactions among particles. In this talk I will present a method to generate multipartite-entangled states using sparse interaction graphs featuring only a logarithmic number of couplings per particle. I will show that specific sparse graphs with long-range interactions can approximate the dynamics of all-to-all spin models, such as the one-axis twisting model, even for large system sizes. The resulting sparse coupling graphs and protocol can also be efficiently implemented using dynamic reconfiguration of atoms in optical tweezers. If time allows, I will discuss a novel approach to perturbatively study the emergence of collective dynamics in spin systems by leveraging the irreducible representations of SU(2).

**Yihui Quek** (Massachusetts Institute of Technology) - Chaos at the limits of computation

Could quantum many-body physics look different to a computationally-bounded observer? This is a central question confronting modern physics as it develops an increasing reliance on computation and big data. We have a good understanding of the information-theoretic limits of quantum information processing, but much less so the limits imposed by bounded computation -- the need to complete the computation in time scaling at most polynomially with the size of the system. One phenomenon that might look very different to such an observer is quantum chaos: while classical chaos theory is well-established, its quantum counterpart remains more ambiguous. As a consequence, quantum chaotic Hamiltonian dynamics is primarily diagnosed via indirect probes, such as the out-of-time-ordered correlator.

I will present work that constructs ensembles of 'pseudochaotic' Hamiltonians that are both computational and statistical spoofers of Gaussian Unitary Ensemble (GUE) Hamiltonians, regarded as a canonical example of chaotic dynamics. Yet, they lack all conventional signatures of chaos, and this has implications for what chaotic probes can actually diagnose.

**Invited Talks**

**Neil Dowling** (University of Cologne) - Bridging Entanglement and Magic Resources through Operator Space

Local operator entanglement (LOE) dictates the complexity of simulating Heisenberg evolution using tensor network methods, and serves as a strong dynamical signature of quantum integrability and information scrambling. I will discuss how LOE is also sensitive to how non-Clifford a unitary is: its magic resources. In particular, I will show that LOE is always upper-bound by three distinct magic monotones: T-count, unitary nullity, and the recently introduced operator stabilizer Rényi entropy. Moreover, in the average case for large, random circuits, LOE and magic monotones approximately coincide. Our results imply that an operator evolution that is expensive to simulate using tensor network methods must also be inefficient using both stabilizer and Pauli truncation methods. Moreover, based on a well-founded conjecture about the scaling of LOE in many-body systems, our bounds also indicate a direct relation between quantum chaos and classical simulability. Entanglement in operator space therefore measures a unified picture of non-classical resources, in stark contrast to the Schrödinger picture.

**Sridevi Kuriyattil** (University of Oxford) - Quantum Information Scrambling in Tunable Range Quantum Spin Models

Quantum information scrambling refers to the spreading of initially localised information across a system’s many degrees of freedom, generating many-body entangled states. The fastest known scramblers achieve this at a timescale that grows logarithmically with the system size N and black holes are conjectured to saturate this bound. Such fast scramblers are also potentially useful for generating resource states within the system’s coherence time. In this work, we investigate efficient entanglement generation using models with tunable-range interactions, focusing on sparse coupling graphs that interpolate between different geometries with varying notions of locality. We show that this crossing between the geometries leads to a dynamical phase transition, marking the onset of fast scrambling in quantum circuits with different levels of long-range connectivity. This enables the identification of regimes where resource states can be generated on timescales of O(logN) allowing the relevant system sizes to grow exponentially with coherence time. We further demonstrate the utility of states generated from these sparse coupling graphs for quantum-enhanced metrology, and propose models to implement both the dynamical transition and the generation of metrologically relevant states in neutral atom arrays using tweezer-assisted shuffling operations.

**Álvaro Yángüez** (Sorbonne Université) - Quantum pseudoresources imply cryptography

While one-way functions (OWFs) serve as the minimal assumption for computational cryptography in the classical setting, in quantum cryptography, we have even weaker cryptographic assumptions such as pseudo-random states, and EFI pairs, among others. Moreover, the minimal assumption for computational quantum cryptography remains an open question. Recently, it has been shown that pseudoentanglement is necessary for the existence of quantum cryptography (Goulão and Elkouss 2024), but no cryptographic construction has been built from it.

In this work, we study the cryptographic usefulness of quantum pseudoresources —a pair of families of quantum states that exhibit a gap in their resource content yet remain computationally indistinguishable.

We show that quantum pseudoresources imply a variant of EFI pairs, which we call EPFI pairs, and that these are equivalent to quantum commitments and thus EFI pairs. Our results suggest that, just as randomness is fundamental to classical cryptography, quantum resources may play a similarly crucial role in the quantum setting.

Finally, we focus on the specific case of entanglement, analyzing different definitions of pseudoentanglement and their implications for constructing EPFI pairs. Moreover, we propose a new cryptographic functionality that is intrinsically dependent on entanglement as a resource.