Quantum Information and the Frontiers of Quantum Theory

Every day starts with a welcoming coffee 09:30–10:00.

**Monday June 27th: quantum computing**

10:00–11:30 David Sutter, *Quasiprobability simulation for error mitigation and circuit knitting*

11:30–13:00 Daniel Stilck França, *Limitations of variational quantum algorithms: a quantum optimal transport approach*

14:30–16:00 Jonas Haferkamp, *On the growth of quantum complexity in random quantum circuits*

16:00–17:00 Michał Oszmaniec, *Saturation and Recurrence of Complexity in Random Quantum Circuits*

17:00–17:30 Arash Ahmadi, *Quantifying quantum computational complexity via information scrambling*

**Tuesday June 28th: spacetime and quantum theory**

10:00–13:00 Freek Witteveen, *Quantum information in holographic gravity*

14:30–17:00 Mischa Woods, *Quantum clocks: from mathematical formulation to quantum advantage*

17:00–17:30 Carlo Cepollaro, *Quantum generalisation of Einstein's Equivalence Principle can be verified with entangled clocks as quantum reference frames*

19:00–21:00 Banquet

**Wednesday June 29th: observer physics; contributed talks**

10:00–11:30 Nuriya Nurgalieva, *Testing quantum theory with thought experiments*

11:30–13:00 Alexandre Feller, *Emergence of classicality from information within a quantum world*

14:30–16:00 Yihui Quek, *How to learn a quantum state (and how not to)*

16:30–17:00 Victor Gitton, *Outer approximations of classical multi-network correlation*

17:00–17:30 Nathanaël Eon, *A relativistic discrete spacetime formulation of 3+1 QED*

### Thursday June 30th: Generalized probabilistic theories; contributed talks

10:00–12:30 Ravi Kunjwal, *A beginner's guide to the landscape of generalized probabilistic theories (GPTs)*

12:30–13:00 Nicolás Medina Sánchez, *Information-theoretic foundations of quantum statistics*

14:30–15:30 Antoine Marquet, *Preventing phase flip errors in cat qubits encoded in a superconducting cavity*

16:00–17:30 Short presentations (10 minutes)

- Denis Rochette, *A geometrical description of the universal* $1 \to 2$ *asymmetric quantum cloning region*
- Mizanur Rahaman, *Counterexamples to the extendibility of positive unital norm-one maps*
- Faedi Loulidi, *Measurement incompatibility vs. Bell non-locality: an approach via tensor norms*
- Yao Ma, *Hybrid PUF: A Novel Way to Enhance the Security of Classical PUFs*
- Armando Angrisani, *Differential Privacy Amplification in Quantum and Quantum-inspired Algorithms*

# Monday 27th

David Sutter, *Quasiprobability simulation for error mitigation and circuit knitting*

**Abstract.** Suppose we want to perform a quantum operation $E$ but we only have access to a set of instruction $(F_i)_i$. In case we find real coefficients $a_i$ such that $E(\cdot) = \sum_i a_i F_i(\cdot)$, we can simulate correct expectation values of $E$ by probabilistically sampling expectation values from $F_i$ at the cost of a sampling overhead scaling as $\sum_i |a_i|$. This idea is called "quasiprobability simulation" and has gained much interested in the fields of classical simulation algorithms and error mitigation. In this talk, I will present two novel applications of this method. First I discuss how to use it for removing errors in noisy circuits where the Clifford gates are protected by error correction and the more complicated T-gates are protected via error mitigation. Secondly I show how quasiprobability simulation can be used for running a nonlocal computation locally. The talk is based on `https://arxiv.org/abs/2103.04915` and `https://arxiv.org/abs/2205.00016`

Daniel Stilck França, *Limitations of variational quantum algorithms: a quantum optimal transport approach*

**Abstract.** Joint work with: Giacomo De Palma, Milad Marvian, Cambyse Rouzé `quant-pharXiv:2204.03455v1`

The impressive progress in quantum hardware of the last years has raised the interest of the quantum computing community in harvesting the computational power of such devices. However, in the absence of error correction, these devices can only reliably implement very shallow circuits or comparatively deeper circuits at the expense of a nontrivial density of errors. In this work, we obtain extremely tight limitation bounds for standard NISQ proposals in both the noisy and noiseless regimes, with or without error-mitigation tools. The bounds limit the performance of both circuit model algorithms, such as QAOA, and also continuous-time algorithms, such as quantum annealing. In the noisy regime with local depolarizing noise p, we prove that at depths $L = O(p^{-1})$ it is exponentially unlikely that the outcome of a noisy quantum circuit outperforms efficient classical algorithms for combinatorial optimization problems like Max-Cut. Although previous results already showed that classical algorithms outperform noisy quantum circuits at constant depth, these results only held for the expectation value of the output. Our results are based on newly developed quantum entropic and concentration inequalities, which constitute a homogeneous toolkit of theoretical methods from the quantum theory of optimal mass transport whose potential usefulness goes beyond the study of variational quantum algorithms.

Jonas Haferkamp, *On the growth of quantum complexity in random quantum circuits*

**Abstract.** Quantifying quantum complexity is a key problem in various subfields of science, from quantum computing to black-hole physics. We prove

rigorous bounds about how random quantum circuits' complexity increases. Consider constructing a unitary from Haar-random two-qubit quantum gates. Implementing the unitary requires a circuit of some minimal number of gates - the unitary's circuit complexity. As such this measure quantifies the compressibility of unitaries. We discuss how lower bounds on the circuit complexity can be obtained from partial derandomizations of counting arguments. We prove that the circuit complexity of exact implementation grows linearly in the number of random gates, with unit probability, until saturating after exponentially many random gates. This confirms a conjecture by Brown and Susskind in the affirmative. Moreover, we discuss new lower bounds on robust notions of quantum circuit complexity using unitary $t$-designs.

Michał Oszmaniec, *Saturation and Recurrence of Complexity in Random Quantum Circuits*

**Abstract.** Quantum complexity is a measure of the minimal number of elementary operations required to approximately prepare a given state or unitary channel. Recently, this concept has found applications beyond quantum computing – in studying the dynamics of quantum many-body systems and the long-time properties of AdS black holes. In this context Brown and Susskind conjectured that the complexity of a chaotic quantum system grows linearly in time up to times exponential in the system size, saturating at a maximal value, and remaining maximally complex until undergoing recurrences at doubly-exponential times. In this work we prove the saturation and recurrence of the complexity of quantum states and unitaries in a model of chaotic time-evolution based on random quantum circuits, in which a local random unitary transformation is applied to the system at every time step. Importantly, our findings hold for quite general random circuit models, irrespective of the gate set and geometry of qubit interactions. Our results advance an understanding of the long-time behaviour of chaotic quantum systems and could shed light on the physics of black hole interiors. From a technical perspective our results are based on establishing new quantitative connections between the Haar measure and high-degree approximate designs, as well as the fact that random quantum circuits of sufficiently high depth converge to approximate designs.

Arash Ahmadi, *Quantifying quantum computational complexity via information scrambling*

**Abstract.** The advent of quantum technologies brought forward much attention to the theoretical characterization of the computational resources they provide. One outstanding challenge to such characterization is the mathematical complexity that their evaluation possesses. A method to quantify quantum computational complexity is to use a class of functions called magic monotones, which are, however, notoriously hard and impractical to evaluate. In this work, we provide a new perspective on calculating magic monotones by connecting them to the concept of information scrambling. Specifically, we establish a connection between information scrambling in random quantum circuits and the magic these circuits generate. This connection allows us to establish a novel, experimentally scalable way to approximate magic monotones in an arbitrary Hilbert space dimension and therefore evaluate the amount of quantum resources using out-of-time-order correlator measurements. Furthermore, we exploit our result connecting scrambling and magic to formulate a simple criterion to determine chaoticity of a given Hamiltonian.

# Tuesday 28th

Freek Witteveen, *Quantum information in holographic gravity*
**Abstract.** A fundamental insight in black hole physics is that the entropy of a black hole appears to scale (surprisingly) with the horizon area of the black hole. This has lead to the proposed AdS/CFT correspondence (holographic quantum gravity), which is a model of gravity in which gravity in $d+1$ dimensions is equivalent to a (non-gravitational) quantum theory on the $d$-dimensional boundary of space-time. Over the last two decades it has become clear that quantum information theory plays a crucial role in this correspondence, leading to important progress in understanding holographic quantum gravity. Loosely, one can say that the coherence of space in the gravitational theory is equivalent to entanglement in the boundary theory. In this lecture I will try to explain the correspondence between geometric aspects of the gravity theory and information theoretic quantities in the boundary theory, using simple toy models and keeping prerequisites to a minimum.

Mischa Woods, *Quantum clocks: from mathematical formulation to quantum advantage*
**Abstract.** Quantum clocks (also refereed to as "ticking clocks" by some authors) are quantum analogues of classical clocks, i.e. devices which autonomously emit ticks at approximately regular intervals. Unlike for classical clocks, where both the register (i.e. the clockface) and the clockwork are classical, in a quantum clock only the register is classical. A clock is very accurate if its ticks are uniformly distributed over time. An important task is to characterize how accurate a clock can be as a function of relevant parameters such as dimension or energy and answer questions such as is there a quantum advantage to timekeeping? A selected subset of references are

- Autonomous quantum clocks: does thermodynamics limit our ability to measure time? `https://doi.org/10.1103/PhysRevX.7.031022`,
- Quantum clocks are more precise than classical ones. `https://doi.org/10.1103/PRXQuantum.3.010319`,
- The thermodynamics of clocks. `https://doi.org/10.1080/00107514.2020.1837471`,
- Autonomous quantum machines and the finite sized Quasi-Ideal clock. `https://doi.org/10.1007/s00023-018-0736-9`

Carlo Cepollaro, *Quantum generalisation of Einstein's Equivalence Principle can be verified with entangled clocks as quantum reference frames*
**Abstract.** The Einstein Equivalence Principle states the equivalence of physics in every locally inertial frame. When the particles involved in the test exhibit quantum properties, it is unknown whether this principle still holds. A possibility introduced in arXiv:2012.13754 [arxiv.org] is that the EEP holds in a generalized form for particles having an arbitrary quantum state, using the concept of Quantum Reference Frame (QRF). QRFs are reference frames associated to quantum particles that can be delocalized: they were introduced with the idea that reference frames are physical system, and eventually every physical system must be treated quantum mechanically. Our argument rests on the use of Spacetime Quantum Reference Frame (SQRF), namely quantum reference frames associated to particles that move in a curved spacetime, with atomic clocks as internal degree of freedom. We show that two entangled atomic clocks can be used to test the extended principle, due to the proper time difference accumulated in two branches of an interferometer in a gravitational field, that generates gravitational time dilation in the two branches.

## Wednesday 29th

Nuriya Nurgalieva, *Testing quantum theory with thought experiments*
**Abstract.** Quantum mechanics is one of our most successful physical theories; its predictions agree with experimental observations to an extremely high accuracy. However, the bare formalism of quantum theory does not provide straightforward answers to seemingly simple questions: for example, how should one model systems that include agents who are themselves using quantum theory? These foundational questions may be investigated with a theorist's tool – the thought experiment. In this talk, we will go through a state-of-the-art overview on quantum thought experiments involving observers, from the basic Wigner's friend to the recent Frauchiger-Renner setup, and introduce a software package where one can design and run simulations of such thought experiments on a quantum computer. We will also discuss fundamental properties of the thought experiments where agents come to a logical contradiction, and their relation to contextuality.

Alexandre Feller, *Emergence of classicality from information within a quantum world*
**Abstract.** Understanding the emergence of a classical picture within a quantum universe is one of the key physics questions related to the fondations of quantum theory. The developments of quantum information and communication theory are shifting our views about it by advocating on an agent-based approach focused on the measuring, computing and communication ressources available to many observers probing the information flow from the system to its environment. Classicality is then viewed as a specific form of the many-body correlations within this complex quantum observer network.

In this tutorial, I will describe these recent evolutions about the quantum-to-classical transition. The overall question we will try to clarify is how do we characterize the ability for many observers to reconstruct a classical picture using quantum information notions. I will start from the standard approach of decoherence and open quantum systems, still widely used to study experiments, and build up to the more precise quantum Darwinism picture where many observers and quantum information are the lead actors.

Yihui Quek, *How to learn a quantum state (and how not to)*
**Abstract.** Learning an unknown $n$-qubit quantum state is a fundamental challenge in quantum computing. Full tomography, however, requires exponential-in-$n$ many copies of $\rho$ for a good estimate. Is it possible to circumvent this exponential tax on resources? We consider two variants of this question:

1. "Pretty-good tomography" (based on `https://arxiv.org/abs/2102.07171`, NeurIPS 2021 (Spotlight)): Aaronson and others introduced several "reduced" models of learning quantum states which impose weaker requirements on the learner: PAC-learning, shadow tomography for learning "shadows" of a quantum state, online learning, whose complexities scale only linearly in n. We show implications and reductions between the many models in this menagerie, and further introduce a combinatorial parameter that characterizes the complexity of learning. As an application, we improve shadow tomography (for classes of quantum states).

2. Probabilistic modelling (based on `https://arxiv.org/abs/2110.05517` and ongoing work): Deep generative models have recently empowered many impressive scientific feats, ranging from predicting protein structure to atomic accuracy (Alpha-Fold) to achieving human-level language comprehension (GPT-3). At the heart of these models is the question: by drawing very few samples from a probability distribution, can we learn an algorithm that generates more samples from the same distribution? Even more intriguingly: could there be a quantum advantage for such a task? We present both go and no-go results for this setting.

Victor Gitton, *Outer approximations of classical multi-network correlation*
**Abstract.** Bell's inequalities characterize the set of achievable outcome distributions in networks of agents sharing a classical random variable. As such, they provide simple means to prove that a probability distribution that is achievable in a network via quantum measurements of a quantum shared resource is incompatible with a realization in the same network but via a classical random variable. Recent research efforts have been dedicated to generalizing this discussion to networks featuring several independent classical or quantum resources that are each accessible to a subset of agents only. In this context, proving that a distribution is incompatible with a realization in a classical network becomes much harder. One of the most useful tool giving access to such proofs is the inflation technique. It has been proven recently that the inflation technique in

fact generates a convergent set of finer and finer outer approximations of the outcome distributions compatible with a given network. In this work, I propose an alternative formulation of the inflation technique that makes the convergence proof more intuitive and visual, and that allows easily to extend it to the case of networks where several agents are constrained to use the same strategy (i.e., response function). This alternative formulation amounts to asking the agents in the network to try to achieve a task that is related to the original classical feasibility task but in which additional resources and additional constraints are introduced, and is in that sense operational and agent-centered.

Nathanaël Eon, *A relativistic discrete spacetime formulation of* $3+1$ *QED*
**Abstract.** This work provides a relativistic, digital quantum simulation scheme for $3+1$ quantum electrodynamics (QED), based on a discrete spacetime formulation of theory. It takes the form of a quantum circuit, infinitely repeating across space and time, parameterized by the discretization step $\Delta_t = \Delta_x$. Strict causality is ensured as circuit wires coincide with the lightlike worldlines of QED; simulation time under decoherence is optimized. The construction replays the logic that leads to the QED Lagrangian. Namely, it starts from the Dirac quantum walk, well-known to converge towards free relativistic fermions. It then extends the quantum walk into a multi-particle sector quantum cellular automata in a way which respects the fermionic anti-commutation relations and the discrete gauge invariance symmetry. Both requirements can only be achieved at cost of introducing the gauge field. Lastly the gauge field is given its own electromagnetic dynamics, which can be formulated as a quantum walk at each plaquette.

## Thursday 30th

Ravi Kunjwal, *A beginner's guide to the landscape of generalized probabilistic theories (GPTs)*
**Abstract.** Quantum theory is intrinsically probabilistic: the mathematical structure of Hilbert spaces makes contact with experiments via probabilities predicted by the Born rule. However, there is no a priori reason why we must arrange our expectations of what happens in an experiment around the Born rule. The world could have been different, with a different type of probability calculus governing the behaviour of experiments. Generalized probabilistic theories allow us to express this possibility in a mathematically rigorous manner. They provide a mathematical landscape within which, in particular, quantum and classical probabilistic theories can be situated. In doing so, they allow us to better understand the probabilistic features of quantum theory that make it unique within this landscape. They also allow us to understand the information-theoretic properties of probabilistic theories from first principles. This tutorial aims at a basic introduction to the framework of GPTs that is accessible to an interdisciplinary audience of mathematicians and physicists (theoretical and experimental). The primary goal of this tutorial is to serve as a beginner's guide

that the user might find useful in navigating the rich landscape of GPTs based on their specific interests.

Nicolás Medina Sánchez, *Information-theoretic foundations of quantum statistics*
**Abstract.** Indistinguishable quantum particles manifest only two types of statistics: bosonic and fermionic, characterized by the exchange symmetry of their associated quantum states. So far, all attempts to explain the origin of these symmetries resort on oblivious assumptions added to the abstract quantum formalism (e.g. dimensionality of the configuration space). Hereby we introduce an information-theoretic study of particle statistics in the space of abstract modes. We show that there are infinitely many statistics compatible with unitary symmetry and a notion of locality. In an exercise of reverse engineering we will discuss the possible implications of these new statistics as a consequence of the topological structure of the configuration space.

Antoine Marquet, *Preventing phase flip errors in cat qubits encoded in a superconducting cavity*
**Abstract.** Because of their coupling to the environment, physical qubits are prone to errors due to decoherence, making it necessary to use quantum error correction (QEC) protocols to pre- serve their quantum information. In this context, new approaches emerged using Bosonic modes where the information is delocalized across the phase space of a cavity, among which the GKP code or the Cat code. The latter uses superpositions of coherent states to encode the quantum information, and can be efficiently protected against bit flips errors using a dissipation mechanism that exchanges pairs of photons with the cavity. Different methods have then been proposed to correct for the remaining phase flips, mainly caused by the loss of single photons inside the cavity. A first possibility which I'll present, currently explored in Alice & Bob, is to use a repetition code of cats qubits. Each cat is then naturally protected against bit flips errors, and the repetition level of protection then allows to detect and correct phase flips. The challenge of this architecture however is to simultaneously control several cats with a good fidelity, as well as designing a universal set of bias preserving gates which won't transform phase flip errors into bit flips, which could then propagate to the rest of the system. An alternative scheme currently being explored in our group is to use a dissipative process that autonomously stabilizes states with a given parity. Similar to Gertler et al., we couple a superconducting cavity to a transmon, itself coupled to a buffer. By using two combs, temporally shifted from one another, we then transfer a photon from the cavity to the buffer whenever a Fock state with an unwanted parity is populated in the cavity. Doing so improves the lifetime of the Fock states with the desired parity, and should provide a way to protect cat qubits against phase flips errors.