Book of Abstracts

Complex Systems: Quantum Information and Computation

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Invited Talks

Shedding Light on Nuclear Spins: Through the looking-glass, and what we found there

Mete Atature

Cavendish Laboratory, University of Cambridge

Optically active spins in solids are often considered prime candidates for scalable and feasible quantum-optical devices. Numerous material platforms including diamond, semiconductors, and atomically thin 2d materials are investigated, where each platform brings their own advantages along with their challenges. Semiconductor quantum dots are the current state-of-the-art for optical properties such as tuneability, brightness and indistinguishability. Their nickname "artificial atom" was coined historically to highlight how similar they can be to isolated single atoms, but in fact they are far from the realisation of a simple two-level system. The inherently mesoscopic nature of a quantum dot leads to a multitude of dynamics between spins, charges, vibrations, and light. In particular, it offers a unique realisation of a tripartite interface between light, a single proxy qubit (electron spin) and an isolated spin ensemble. Ability to control these constituents and their mutual interactions creates opportunities to realise an optically controllable ensemble of 50,000 spins. In this talk, I will present the decade-long journey from treating the quantum dot nuclei as noise to the observation of their collective magnon modes and eventually to their tuneable quantum correlations, all witnessed via a single electron spin driven by light.

Continuous-time Quantum Walk recognition through machine learning

Ilaria Gianani[1] and Claudia Benedetti

[1]Università degli Studi Roma Tre

Understanding how the information is spread especially across large networks is of paramount importance for many applications, such as quantum communications, quantum computation and energy transport in light-harvesting systems. A necessary step before tackling real complex systems is that of simulating their behaviour in order to develop a complete framework. Control of experimental simulations may need to be performed through features that do not trivially relate to the hamiltonian parameters describing a quantum walk, allowing full control of the walker only in extremely simple instances. This poses a further question compared to the mere characterisation of the network: can we trace back and identify what evolution the network has incurred, starting from the experimental probability measured at different times?

During this talk we will try answering this question, focusing on the development of machine learning algorithms. The problem we pose is twofold: we first explore how to retrieve the graph topology, then how to perform a multiparameter estimation of the couplings. Our results present a preliminary step towards the development of new paradigms for transport of quantum information across large networks.

Quantum dynamics of small quantum thermal machines

Géraldine Haack

University of Geneva

Minimal models for quantum thermal machines are central to understand energy exchanges at the quantum scale and the intimate connection between quantum thermodynamics and quantum information theory. In particular, one would like to determine whether quantum features, like entanglement, interactions and quantum statistics, can be beneficial to the efficiency of a thermal machine made of few quantum constituents. This research direction becomes even more fascinating in view of recent experimental progresses towards manipulating out-of-equilibrium multipartite quantum systems, allowing for new designs and investigations of quantum (complex) thermal machines. In this talk, I will present some of our latest results concerning the advantages that open quantum systems can offer towards heat management at the nanoscale, including storing energy, controlling the flow of energy and optimization of dissipative flows.

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[1] Khandelwal et al., PRX Quantum 2, 040346 (2021).
[2] Seah et al., PRL 127, 100601 (2021).
[3] Khandelwal et al., arXiv:2208.10809 (2022).

Unlocking practical quantum advantage with near-term quantum computers

Sabrina Maniscalco

Algorithmiq Oy

Today's quantum computers are imperfect. They are made of dozens of qubits that can be prepared in highly non-classical states but, being very sensitive to noise, their ability to preserve quantum properties is very limited. Noise not only arises from the interaction with the external environment, but encompasses all the imperfections in the sophisticated quantum hardware and control system. This is why, despite the discovery of algorithms that in principle would allow us to simulate interesting and currently intractable problems in chemistry and materials, applications to industrially relevant problems seem out-of-reach. Therefore, several quantum computing players are shifting their attention away from near-term quantum computers and towards fault-tolerant devices.

In this talk I will show that, contrarily to what is largely believed, quantum algorithms on near-term quantum computers can lead to quantum advantage already now. The key ingredient to unlock quantum advantage in noisy devices is the use of informationally complete generalised measurements (IC POVMs) [1,2]. Our results show how our hybrid variational quantum-classical algorithms using IC data allow for unprecedented noise attenuation [3], execution time reduction [1,2], and efficient ansatz generation.

The combination of these three achievements makes current quantum computers able to show quantum advantage for quantum chemistry problems in the very near future.

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[1] "Learning to Measure: Adaptive Informationally Complete Generalized Measurements for Quantum Algorithms", Guillermo García-Pérez, Matteo A. C. Rossi, Boris Sokolov, Francesco Tacchino, Panagiotis Kl. Barkoutsos, Guglielmo Mazzola, Ivano Tavernelli, Sabrina Maniscalco, PRX Quantum 2, 040342 (2021).

[2] "Adaptive POVM implementations and measurement error mitigation strategies for near-term quantum devices", Adam Glos, Anton Nykänen, Elsi-Mari Borrelli, Sabrina Maniscalco, Matteo A. C. Rossi, Zoltán Zimborás, Guillermo García-Pérez, arXiv:2208.07817

[3] "Virtual linear map algorithm for classical boost in near-term quantum computing", Guillermo García-Pérez, Elsi-Mari Borrelli, Matea Leahy, Joonas Malmi, Sabrina Maniscalco, Matteo A. C. Rossi, Boris Sokolov, Daniel Cavalcanti, arXiv:2207.01360

Quantum Computing on Complex Networks

Yasser Omar
PQI – Portuguese Quantum Institute & CeFEMA, IST, University of Lisbon

In this talk, I will discuss how it is possible to perform optimal quantum computation in complex networks, as well as explore the potential of quantum computation for link prediction.

Experimental quantum communication enhancement by superposing trajectories

Giulia Rubino[1], Lee A. Rozema, Daniel Ebler, Hlér Kristjánsson, Sina Salek, Philippe Allard Guérin, Alastair A. Abbott, Cyril Branciard, Časlav Brukner, Giulio Chiribella, and Philip Walther

[1]University of Bristol

In quantum communication networks, wires represent well-defined trajectories along which quantum systems are transmitted. In spite of this, trajectories can be used as a quantum control to govern the order of different noisy communication channels, and such a control has been shown to enable the transmission of information even when quantum communication protocols through well-defined trajectories fail. This result has motivated further investigations on the role of the superposition of trajectories in enhancing communication, which revealed that the use of quantum control of parallel communication channels, or of channels in series with quantum-controlled operations, can also lead to communication advantages. Building upon these findings, in this talk I will present experimental and numerical comparisons among the different ways in which two trajectories through a pair of noisy channels can be superposed. I will observe that, within the framework of quantum interferometry, the use of channels in series with quantum-controlled operations generally yields the largest advantages. These results contribute to clarify the nature of these advantages in experimental quantum-optical scenarios, and showcase the benefit of an extension of the quantum communication paradigm in which both the information exchanged and the trajectory of the information carriers are quantum.

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[1] Phys. Rev. Research 3, 013093 (2021).

Contributed Talks

Bounding the Minimum Time of a Quantum Measurement

Nathan Shettell, Federico Centrone[1], and Luis Pedro García-Pintos
[1]ICFO, Institut de Ciències Fotòniques

Measurements take a singular role in quantum theory. While they are often idealized as an instantaneous process, this is in conflict with all other physical processes in nature. Here, we adopt a standpoint where the interaction with an environment is a crucial ingredient for the occurrence of a measurement. Within this framework, we derive lower bounds on the time needed for a measurement to occur. We evaluate our bound in two examples where the environment is modelled by harmonic oscillators and the measurement apparatus is modelled by spins or bosons. We further discuss possible experimental implementations of the dynamics of a measurement induced by complex environments.

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[1] ArXiv:2209.06248 (2022)

Noise-induced network topologies

Frederic Folz[1], Kurt Mehlhorn, and Giovanna Morigi
[1]Theoretische Physik, Universität des Saarlandes

Biologically-inspired network models provide a powerful framework for optimization algorithms. One prominent algorithm simulates the networks of filaments built by the unicellular organism Physarum polycephalum. Inspired by nature, we analyse the networks predicted by this dynamics in the presence of stochastic forces simulating a thermal environment. The resulting networks exhibit different topologies as a function of the temperature, which are generally multistable. Remarkably, the system converges to the most robust configuration at non-zero temperatures exhibiting a resonant-like behavior. This configuration is reached with the maximal convergence rate and is not found by the deterministic algorithm. Our results show that stochastic dynamics could qualitatively increase the computational power of optimization algorithms by actively modifying the landscape of the minima corresponding to the sought solutions.

[1] arXiv:2207.09111.

Photonic platform for real time quantum reservoir computing

Jorge García-Beni[1], Gian Luca Giorgi, Miguel C. Soriano and Roberta Zambrini
[1] IFISC (UIB-CSIC), Institut de Física Interdisciplinària i Sistemes Complexos

Reservoir Computing is a Machine Learning paradigm that aims to exploit the information processing capabilities of dynamical systems to solve non-trivial temporal tasks. Our work revolves around Quantum Reservoir Computing (QRC), in which quantum systems are used as substrates. Concretely, we focus on quantum photonic systems. In this field, several opportunities and challenges arise [1]. One of those challenges comes from the stochastic nature of quantum measurements: the relevant information for QRC protocols is found in the expected values of the substrate observables, which makes it challenging to process information in real time (the task is performed while the input signal is being recorded). We have proposed a quantum photonic platform to overcome this limitation [2]. It is an optical platform in which a classical input signal is encoded in the quantum fluctuations of vacuum states inside an optical pulse. This encoded signal is coupled (via a beam-splitter) to a feedback loop of circulating pulses travelling through an optical fiber, yielding an output signal which is continuously monitored. One nonlinear crystal is added inside the feedback loop, which applies non-trivial dynamics to the recirculating light. This makes the measured signal a complex nonlinear function of the history of classical inputs, and so the platform can be trained to perform non-trivial tasks on generic classical temporal data. The expected values of the observables can be obtained in by generating a physical ensemble of identical pulses inside the fiber loop. These ensemble of pulses is weakly monitored and the ensemble average among them yields the desired outcome signal in real time. The platform has been theoretically conceived to be experimentally viable with current technology. We have studied how this platform performance drops under the effect of readout noise and how it can be mitigated by the suitable tuning of some key parameters.

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[1] P. Mujal, R. Martínez-Peña, J. Nokkala, J. García-Beni, G. L. Giorgi, M. C. Soriano and R. Zambrini (2021). Opportunities in quantum reservoir computing and extreme learning machines. Advanced Quantum Technologies, 4(8), 2100027.

[2] J. García-Beni, G. L. Giorgi, M. C. Soriano and R. Zambrini (2022). arXiv:2207.14031.

Quantum Simplicity: Can things look simpler through the lens of Quantum Theory?

Mile Gu

Nanyang Quantum Hub, School of Physical and Mathematical Sciences, Nanyang Technological University

Complexity and quantum science previously appeared to two fields that bear little relation. One deals with the science of macroscopic reality – seeking the understand and predict the behavior of large complex systems in the everyday world. Quantum theory, on the other hand, deals with particles at the microscopic level, and is usually considered limited to the domain of individual photons and atoms. Yet, different as they appear, there is growing evidence that the science of the very small may help us better understand that of the very large. Here I give a lightning tour of research at the quantum and complexity science initiative in Singapore - where we see that the unique properties of quantum mechanics can fundamentally change what we consider to be complex. Emphasize will be on recent results, where we illustrate that quantum agents may extend significant less resources - in memory or energy - to executing complex adaptive tasks in real-time.

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[1] A practical, unitary simulator for non-Markovian complex processes. Phys. Rev. Lett. 120, 240502

[2] Quantum adaptive agents with efficient long-term memories, Phys. Rev. X 12, 011007

On characterising the capabilities of quantum reservoir computing

Luca Innocenti[1], Ivan Palmisano, Salvatore Lorenzo, Alessandro Ferraro, Mauro Paternostro, and Massimo Palma

[1]Università di Palermo

Quantum reservoir computers (QRC) and quantum extreme learning machines (QELM) aim to efficiently post-process the outcome of fixed — generally uncalibrated — quantum devices to solve tasks such as the estimation of the properties of quantum states. A characterisation of their potential and limitations, currently missing in the literature, would enable the full deployment of such approaches to problems of system identification, device performance optimization, and state or process reconstruction. We present a framework to model QRCs and QELMs, showing that they can be concisely described via single effective measurements, and provide an explicit characterisation of the information exactly retrievable with such protocols. We furthermore find a close analogy between the training process of QELMs and that of reconstructing the effective measurement characterising the given device. Our analysis paves the way to a more thorough understanding of the capabilities and limitations of both QELMs and QRCs, and has the potential to become a powerful measurement paradigm for quantum state estimation that is more resilient to noise and imperfections.

Quantum Reservoir Computing for Speckle Disorder Potentials

Pere Mujal

IFISC (UIB-CSIC), Institut de Física Interdisciplinària i Sistemes Complexos

Quantum reservoir computing is a machine learning approach designed to exploit the dynamics of quantum systems with memory to process information. As an advantage, it presents the possibility to benefit from the quantum resources provided by the reservoir combined with a simple and fast training strategy, as fitting a linear model. In this work [1], the quantum reservoir computing approach consisting of a qubit network is introduced to make predictions on the ground state energy of different speckle disorder potentials as an alternative to classical machine learning methods based on convolutional neural networks [2]. In this way, a quantum system in the presence of disorder that originates the Anderson localization phenomenon is studied by exploiting the memory and computational capabilities provided by an additional quantum system.

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[1] P. Mujal, Condens. Matter 7(1), 17 (2022).

[2] P. Mujal, A. Martínez Miguel, A. Polls, B. Juliá-Díaz, and S. Pilati, SciPost Phys. 10, 73 (2021).

Why the field of quantum complex networks is not a lake, it's an ocean

Johannes Nokkala[1] and Ginestra Bianconi

[1]University of Turku

Network theory has been a prominent tool for taming the complexity of both physical and abstract systems in various disciplines, including also quantum physics. It has been applied to, e.g., investigate the performance and structure of theoretical communication networks dealing with quantum information, to find useful and informative network representations for quantum states and to optimize properties of interest of quantum systems with a network structure. Overall, the field of quantum complex networks remains somewhat fragmented however, with little interaction between what might be thought of as its subfields. Despite even significant differences between the various types of networks there might very well be potential for cross-fertilization, yet they are rarely even presented together.

In my talk I give a brief and compact tour of the field based on an upcoming topical review. I will cover pertinent examples and applications related to quantum communication networks, emergent quantum networks and quantum systems as networks, drawing attention to connections and similarities between them where they appear and emphasizing the broader context of quantum complex networks. Technical details and specialized jargon will be avoided in favor of presenting the central concepts and key ideas in the language all cases share: the language of networks.

A hybrid classical-quantum approach to speed-up Q-learning

A. Sannia, A. Giordano, N. Lo Gullo, C. Mastroianni, F. Plastina[1]
[1]Dipartimento di Fisica, Università della Calabria

A classical-quantum hybrid approach to computation is described, allowing for a quadratic performance improvement in the decision process of a learning agent. In particular, a quantum routine is described, to encode on a quantum register the probability distributions that drive action choices in a reinforcement learning set-up. This routine can be employed by itself in several contexts where decisions are driven by probabilities. After introducing the algorithm and formally evaluating its performance, in terms of computational complexity and maximum approximation error, we discuss in detail how to exploit it in the Q-learning context.

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[1] Sannia et al., https://arxiv.org/abs/2205.07730

The role of dissipation in Quantum Reservoir Computing

Antonio Sannia[1], Rodrigo Martínez-Peña, Miguel C. Soriano, Gian Luca Giorgi, Roberta Zambrini

[1]IFISC (UIB-CSIC), Institut de Física Interdisciplinària i Sistemes Complexos

Dissipation induced by interactions with an external environment, typically hindering the performance of quantum computation, can be turned out as a useful resource. We apply this idea in the field of quantum reservoir computing introducing tunable local losses in spin network models. Our approach based on continuous dissipation is able not only to reproduce the dynamics of the previous proposal of quantum reservoir computing, based on a discontinuous erasing map but also to enhance its performance. Control of the damping rates allows reaching better performances in popular machine learning tasks which concern the capability to linearly and non-linearly process the input history and to forecast chaotic series. Finally, we will formally prove that, under non-restrictive conditions, our dissipative models form a universal class for reservoir computing. It means that considering them, it is possible to approximate any fading memory map with arbitrary precision.

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[1] Keisuke Fujii and Kohei Nakajima, "Harnessing Disordered-Ensemble Quantum Dynamics for Machine Learning", Phys. Rev. Applied 8, 024030 (2017).

[2] Herbert Jaeger. "The "echo state" approach to analysing and training recurrent neural networks-with an erratum note". In: Bonn, Germany: German National Research Center for Information Technology GMD Technical Report 148.34, p. 13 (2001).

Generation of multi-mode CV quantum networks using a femtosecond laser in a single-pass waveguide

David Faisin, Victor Román Rodríguez, Guilherme Luiz Zanin[1], Eleni Diamanti, Nicolas Treps, Valentina Parigi

[1]Laboratoire Kastler Brossel, Sorbonne Université

Complex networks theory can be used to describe a variety of systems that can be represented by graph states that are composed of nodes connected via links to the edges that describe the interactions, such as the internet for example. When including quantum ingredients, we arrive at the complex quantum networks that are resources for measurement-based quantum computation, quantum key distribution, etc.., in this case, the nodes or the network are entangled, i.e. they have correlations. The usual photonic approach for the creation of cluster states is the use of DV (discrete variables) in which different pairs of photons of entangled photons interact to generate the cluster. However, in this approach, the generation of big clusters is challenging given the probabilistic nature of the photon pairs generation, and the format of the cluster is defined by the alignment of the setup. To avoid this problem in this project we use CV (continuous variables), where the entanglement is in between the quadratures of the electromagnetic field. In the CV case, we have an infinite-dimensional Hilbert space that provides a naturally big alphabet to encode quantum information. We generate CV cluster states using a femtosecond laser in the telecommunication wavelength regime using single-pass non-linear waveguides that allow us deterministically produce multimode entangled states. This is the first homodyne measurement of multimode squeezed states in a spontaneous parametric process at telecom wavelengths using a single-pass waveguide. The pulsed multimode states combined with a fast homodyne detection allow us to generate large cluster states that are easily reconfigurable by the use of a pulse shaping technique on the local oscillator, as the homodyne detection is a projective measurement. Exploring these large cluster states in the telecommunication wavelength will allow us to explore quantum communication protocols over medium-range distances.

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[1] New J. Phys. 23 (2021) 043012.

Circuit complexity through phase transitions and its consequences in quantum state preparation

David Zueco

CSIC-Universidad de Zaragoza

How much does it cost to generate a target quantum state from another reference state? This is a rather general question that has been discussed in quantum information for obvious reasons. In quantum computation it is desirable to obtain the result with the minimum set of gates. This number is, roughly speaking, the cost and it is called Complexity [1,2]. In this talk, I will introduce different ways to compute the complexity to prepare the ground states, i.e. the target state is the ground state of a given Hamiltonian. We will be interested in the situation where on the way from the reference to the target we cross a critical point. We will work different examples and draw general consequences. We will calculate exactly the complexity for integrable models, like the anisotropic XY, quasi-soluble like the Dicke model. As well as numerical results for non-integrable Hamiltonians (ZZXZ model). We will discuss general properties through scaling hypotheses and find optimal ways to reach the target state. All this theory will be applied to real algorithms: we will calculate the circuit complexity for varational quantum eigensolvers (VQE) and adiabatic algorithms (with and without shortcuts). As a take home message, we will show universal scaling relationships for circuit complexity. For systems of finite size and depending on the critical exponents, this quantity can be subextensive, extensive or superextensive. In the thermodynamic limit, we will discuss how complexity diverges.

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[1] M. A. Nielsen, M. R. Dowling, M. Gu, and A. C. Doherty, Science 311, 1133 (2006).

[2] Quantum computational complexity from quantum information to black holes and back Shira Chapman and Giuseppe Policastro. The European Physical Journal C volume 82, Article number: 128 (2022).