ICMAT QIT 2023 – Focus Week 2

Talks

- Monday
  - 10:45 **Angela Capel**: Rapid thermalization of spin chain commuting Hamiltonians
  - 12:00 **Bruno Nachtergaele**: Two dimerized gapped ground state phases of O(n) spin chains?
- Tuesday
  - 10:15 **Pieter Naaijkens**: Classification of topologically ordered phases of matter in 2D
  - 12:00 **David Gosset**: On the complexity of quantum partition functions
- Wednesday
  - 10:45 **Toby Cubitt**: Dissipative State Preparation and the Dissipative Quantum Eigensolver
  - 12:00 **Michael Walter**: The minimal canonical form of a tensor network
- Thursday
  - 10:15 **Giacomo De Palma**: The quantum Wasserstein distance of order 1
  - 12:00 **Victor Albert**: Physics of quantum phases of matter from a computer-science perspective
- Friday
  - 10:45 **Kohtaro Kato**: Entanglement bootstrap and the spurious topological entanglement entropy
  - 12:00 **Amanda Young**: On Gapped Ground State Phases of Decorated AKLT Models

Abstacts

Angela Capel: Rapid thermalization of spin chain commuting Hamiltonians

In this talk, we will show that spin chains weakly coupled to a large heat bath thermalize rapidly at any temperature for finite-range, translation-invariant commuting Hamiltonians, reaching equilibrium in a time which scales logarithmically with the system size. This represents an exponential improvement over bounds based on the non-closure of the spectral gap. From a physical point of view, this result rigorously establishes the absence of dissipative phase transition for Davies evolutions over translation-invariant spin chains. It also applies in the case of Symmetry Protected Topological phases where the evolution is respecting the symmetry of the phase, and has wide-ranging applications to the study of many-body in and out-of-equilibrium quantum systems, some of which will be discussed during the talk. This is based on joint work with I. Bardet, L. Gao, A. Lucia, D. Pérez-García and C. Rouzé.

Bruno Nachtergaele: Two dimerized gapped ground state phases of $O(n)$ spin chains?

We consider a family of quantum spin chains with $O(n)$ and translation invariant nearest neighbor interactions and identify two gapped phases in their phase diagram for all $n \geq 3$. For even values of n both phases break the translation invariance down to period 2. We establish that the phases are distinct, investigate their stability, and address the question whether they represent two kinds of dimerization.

Pieter Naaijkens: Classification of topologically ordered phases of matter in 2D

In this talk I will consider topological phases of matter which have what is called long range entanglement (LRE), using an operator algebraic point of view. An interesting aspect is that such states can support quasi-particles with braided statistics, called anyons. In this talk, I will highlight some recent results in the classification of such phases of matter, and state some of the current challenges in the field.

David Gosset: On the complexity of quantum partition functions

Toby Cubitt: Dissipative State Preparation and the Dissipative Quantum Eigensolver

Finding ground states of quantum many-body systems is one of the most important—and one of the most notoriously difficult—problems in physics, both in scientific research and in practical applications. Indeed, we know from a complexity-theoretic perspective that all methods (quantum or classical) must necessarily fail to find the ground state efficiently in general. The ground state energy problem is already NP-hard even for classical, frustration-free, local Hamiltonians with constant spectral gap. For general quantum Hamiltonians, the problem becomes QMA-hard.

Nonetheless, as ground state problems are of such importance, and classical algorithms are often successful despite the theoretical exponential worst-case complexity, a number of quantum algorithms for the ground state problem have been proposed and studied. From quantum phase estimation-based methods, to adiabatic state preparation, to dissipative state engineering, to the variation quantum eigensolver (VQE), to quantum/probabilistic imaginary-time evolution (QITE/PITE).

Dissipative state engineering was first introduced in 2009 by Verstraete, Cirac and Wolf and by Kraus et al. However, it only works for the restricted class of frustration-free Hamiltonians.

In this talk, I will show how to construct a dissipative state preparation dynamics that provably produces the correct ground state for arbitrary Hamiltonians, including frustrated ones. This leads to a new quantum algorithm for preparing ground states: the Dissipative Quantum Eigensolver (DQE). DQE has a number of interesting advantages over previous ground state preparation algorithms:

- The entire algorithm consists simply of iterating the same set of simple local measurements repeatedly.
- The expected overlap with the ground state increases monotonically with the length of time this process is allowed to run.
- It converges to the ground state subspace unconditionally, without any assumptions on or prior information about the Hamiltonian (such as spectral gap or ground state energy bound).
- The algorithm does not require any variational optimisation over parameters.
- It is often able to find the ground state in low circuit depth in practice.
- It has a simple implementation on certain types of quantum hardware, in particular photonic quantum computers.
- It is immune to errors in the initial state.
- It is inherently fault-resilient, without incurring any fault-tolerance overhead. I.e. not only is it resilient to errors on the quantum state, but also to faulty implementations of the algorithm itself; the overlap of the output with the ground state subspace degrades smoothly with the error rate, independent of the total run-time.

I give a mathematically rigorous analysis of the DQE algorithm and proofs of all the above properties, using non-commutative generalisations of methods from classical probability theory.

Michael Walter: The minimal canonical form of a tensor network

Tensor networks have a gauge degree of freedom on the virtual degrees of freedom that are contracted. A canonical form is a choice of fixing this degree of freedom. For matrix product states, choosing a canonical form is a powerful tool, both for theoretical and numerical purposes. On the other hand, for tensor networks in dimension two or greater there is only limited understanding of the gauge symmetry. Here we introduce a new canonical form, the minimal canonical form, which applies to projected entangled pair states (PEPS) in any dimension, and prove a corresponding fundamental theorem. Already for matrix product states this gives a new canonical form, while in higher dimensions it is the first rigorous definition of a canonical form valid for any choice of tensor. We show that two tensors have the same minimal canonical forms if and only if they are gauge equivalent up to taking limits; moreover, this is the case if and only if they give the same quantum state for any geometry. In particular, this implies that the latter problem is decidable - in contrast to the well-known undecidability for PEPS on grids. We also provide rigorous algorithms for computing minimal canonical forms. To achieve this we draw on geometric invariant theory and recent progress in theoretical computer science in non-commutative group optimization. Joint work with Arturo Acuaviva, Visu Makam, Harold Nieuwboer, David Pérez-García, Friedrich Sittner, and Freek Witteveen.

Giacomo De Palma: The quantum Wasserstein distance of order 1

We propose a generalization of the Wasserstein distance of order 1 to the quantum states of n qudits. The proposal recovers the Hamming distance for the vectors of the canonical basis and more generally the classical Wasserstein distance for quantum states diagonal in the canonical basis. We prove a continuity bound for the von Neumann entropy with respect to the proposed distance, which significantly strengthens the best continuity bound with respect to the trace distance. We also propose a generalization of the Lipschitz constant to quantum observables. The notion of quantum Lipschitz constant allows us to compute the proposed distance with a semidefinite program. We prove a Gaussian concentration inequality for the spectrum of quantum Lipschitz observables and a quadratic concentration inequality for quantum Lipschitz observables measured on product states. We apply such inequalities to obtain extremely tight limitation bounds for standard NISQ proposals in both the noisy and noiseless regimes. The bounds limit the performance of both circuit-model algorithms, such as QAOA, and continuous-time algorithms, such as quantum annealing. In the noisy regime with local depolarizing noise p, we prove that at depth O(pˆ-1) it is exponentially unlikely that the outcome of a noisy quantum circuit outperforms efficient classical algorithms for combinatorial optimization problems like Max-Cut.

Victor Albert: Physics of quantum phases of matter from a computer-science perspective

Kohtaro Kato: Entanglement bootstrap and the spurious topological entanglement entropy

In this talk, we introduce the entanglement bootstrap approach to study gapped ground states. In this approach, one starts from a pure state on a two-dimensional spin lattice that satisfy the area law of entanglement, and then one can extract various information of the corresponding topological order behind the system just from consistency equations. The program seems to have succeed in defining anyon charges and fusion rules from entanglement, however the invariance of these concepts under quasi-adiabatic evolutions (constant-depth circuits) has not yet been proven. The main obstacle is the existence of a non-topological contribution, which is called spurious topological entanglement entropy, in the area law. The second half of this talk will focus on such mysterious non-topological correlations.

Amanda Young: On Gapped Ground State Phases of Decorated AKLT Models

In their seminal work, Affleck, Kennedy, Lieb and Tasaki introduced a family of SU(2)-invariant quantum spin models and investigated their ground state properties - including the existence of positive spectral gap above the ground state energy in the thermodynamic limit. They conjectured that if the coordination number of a given regular, translation invariant lattice was sufficiently small, the associated AKLT model would have a positive spectral gap. Otherwise, the model would exhibit Neel order and, hence, be gapless. Decorated versions of AKLT models obtained from replacing edges of lattices with chains of spin-1 particles have also been of interest, e.g., as their ground states constitute a universal quantum computation resource. A natural question, then, is whether or not decorated AKLT models belong to gapped or gapless ground state phases.

In this talk, we consider AKLT models defined on decorated versions of (potentially infinite) simple, connected graphs and show that for sufficiently large decoration, the resulting model belongs to a gapped phase. The proof of this result is based off a modified version of the Tensor Network State approach introduced by Abdul-Rahman et. al. which produces tighter estimates on the minimal decoration required to prove a positive spectral gap. Time permitting, we then turn to the question of the stability of the spectral gap in the presence of small perturbations. In the case of the AKLT model on the decorated hexagonal model, we discuss how to use cluster expansion techniques to prove that the ground states are sufficiently indistinguishable so spectral gap stability results in the spirit of Bravyi, Hastings and Michalakis hold.

This talk is based of joint works with A. Lucia (arXiv:2212.11872), and with A. Lucia and A. Moon (arXiv:2209.01141).