Journal Club, 17th March 2015, James Wootton

Undecidability of the Spectral Gap
Toby Cubitt, David Perez-Garcia, Michael M. Wolf
arXiv:1502.04573 and arXiv:1502.04135

We show that the spectral gap problem is undecidable. Specifically, we construct families of translationally-invariant, nearest-neighbour Hamiltonians on a 2D square lattice of d-level quantum systems (d constant), for which determining whether the system is gapped or gapless is an undecidable problem. This is true even with the promise that each Hamiltonian is either gapped or gapless in the strongest sense: it is promised to either have continuous spectrum above the ground state in the thermodynamic limit, or its spectral gap is lower-bounded by a constant in the thermodynamic limit. Moreover, this constant can be taken equal to the local interaction strength of the Hamiltonian. This implies that it is logically impossible to say in general whether a quantum many-body model is gapped or gapless. Our results imply that for any consistent, recursive axiomatisation of mathematics, there exist specific Hamiltonians for which the presence or absence of a spectral gap is independent of the axioms. These results have a number of important implications for condensed matter and many-body quantum theory.

Gapped and gapless phases of frustration-free spin-1/2 chains
Sergey Bravyi, David Gosset
arXiv:1503.0403

We consider a family of translation-invariant quantum spin chains with nearest-neighbor interactions and derive necessary and sufficient conditions for these systems to be gapped in the thermodynamic limit. More precisely, let ψ be an arbitrary two-qubit state. We consider a chain of n qubits with open boundary conditions and Hamiltonian $H_n(\psi)$ which is defined as the sum of rank-1 projectors onto ψ applied to consecutive pairs of qubits. We show that the spectral gap of $H_n(\psi)$ is upper bounded by $1/(n-1)$ if the eigenvalues of a certain two-by-two matrix simply related to ψ have equal non-zero absolute value. Otherwise, the spectral gap is lower bounded by a positive constant independent of n (depending only on ψ). A key ingredient in the proof is a new operator inequality for the ground space projector which expresses a monotonicity under the partial trace. This monotonicity property appears to be very general and might be interesting in its own right.

Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices
Erez Zohar, J. Ignacio Cirac, Benni Reznik
arXiv:1503.02312

Can high energy physics can be simulated by low-energy, nonrelativistic, many-body systems, such as ultracold atoms? Such ultracold atomic systems lack the type of symmetries and dynamical properties of high energy physics models: in particular, they manifest neither local gauge invariance nor Lorentz invariance, which are crucial properties of the quantum field theories which are the building blocks of the standard model of elementary particles. However, it turns out, surprisingly, that there are ways to configure atomic system to manifest both local gauge invariance and Lorentz invariance. In particular, local gauge invariance can arise either as an effective, low energy, symmetry, or as an "exact" symmetry, following from the conservation laws in atomic interactions. Hence, one could hope that such quantum simulators may lead to new type of (table-top) experiments, that shall be used to study various QCD phenomena, as the con?nement of dynamical quarks, phase transitions, and other effects, which are inaccessible using the currently known computational methods. In this report, we review the Hamiltonian formulation of lattice gauge theories, and then describe our recent progress in constructing quantum simulation of Abelian and non-Abelian lattice gauge theories in 1 + 1 and 2 + 1 dimensions using ultracold atoms in optical lattices.

Thermodynamic universality of quantum Carnot engines
Bartlomiej Gardas, Sebastian Deffner
arXiv:1503.03455

The Carnot statement of the second law of thermodynamics poses an upper limit on the efficiency of all heat engines. Recently, it has been studied whether generic quantum features such as coherence and quantum entanglement could allow for quantum devices with efficiencies larger than the Carnot efficiency. The present study shows that this is not permitted by the laws of thermodynamics. In particular, we will show that rather the definition of heat has to be modified to account for the thermodynamic cost for maintaining coherence and entanglement. Our theoretical findings are numerically illustrated for an experimentally relevant example from optomechanics..

Topological Kondo Effect in Transport through a Superconducting Wire with Multiple Majorana End States
Oleksiy Kashuba and Carsten Timm
Phys. Rev. Lett. 114, 116801

We investigate a system of multiple Majorana states at the end of a topological superconducting wire coupled to a normal lead. For a minimum of three Majorana fermions at the interface, we find nontrivial renormalization physics. Interface tunneling processes can be classified in terms of spin-1/2 and spin-3/2 irreducible representations of the SU(2) group. We show that the renormalization of the tunneling amplitudes belonging to different representations is completely different in that one type is suppressed, whereas the other is enhanced, depending on the sign of the Kondo-type interaction coupling. This results in distinct temperature dependencies of the tunneling current through the interface and different spin polarizations of this current.

Many-Body Localization in Imperfectly Isolated Quantum Systems
Sonika Johri, Rahul Nandkishore, and R.N. Bhatt
Phys. Rev. Lett. 114, 117401

We use numerical exact diagonalization to analyze which aspects of the many-body localization phenomenon survive in an imperfectly isolated setting, when the system of interest is weakly coupled to a thermalizing environment. We show that widely used diagnostics (such as many-body level statistics and expectation values in exact eigenstates) cease to show signatures of many-body localization above a critical coupling that is exponentially small in the size of the environment. However, we also identify alternative diagnostics for many-body localization, in the spectral functions of local operators. Diagnostics include a discrete spectrum and a hierarchy of energy gaps, including a universal gap at zero frequency. These alternative diagnostics are shown to be robust, and continue to show signatures of many-body localization as long as the coupling to the bath is weaker than the characteristic energy scales in the system. We also examine how these signatures disappear when the coupling to the environment becomes larger than the characteristic energy scales of the system.

Solution to the Quantum Zermelo Navigation Problem
Dorje C. Brody and David M. Meier
Phys. Rev. Lett. 114, 100502

The solution to the problem of finding a time-optimal control Hamiltonian to generate a given unitary gate, in an environment in which there exists an uncontrollable ambient Hamiltonian (e.g., a background field), is obtained. In the classical context, finding the time-optimal way to steer a ship in the presence of a background wind or current is known as the Zermelo navigation problem, whose solution can be obtained by working out geodesic curves on a space equipped with a Randers metric. The solution to the quantum Zermelo problem, which is shown here to take a remarkably simple form, is likewise obtained by finding explicit solutions to the geodesic equations of motion associated with a Randers metric on the space of unitary operators. The result reveals that the optimal control in a sense goes along with the wind.

Randomized Benchmarking of Single-Qubit Gates in a 2D Array of Neutral-Atom Qubits
T. Xia, M. Lichtman, K. Maller, A.W. Carr, M.J. Piotrowicz, L. Isenhower, and M. Saffman
Phys. Rev. Lett. 114, 100503

We characterize single qubit Clifford gate operations with randomized benchmarking in a 2D array of neutral atom qubits, and demonstrate global and site selected gates with high fidelity. An average fidelity of $F^2 = 0.9983(14)$ is measured for global microwave driven gates applied to a 49 qubit array. Single site gates are implemented with a focused laser beam to Stark shift the microwaves into resonance at a selected site. At Stark selected single sites we observe $F^2 = 0.9923(7)$ and an average spin flip crosstalk error at other sites of 0.002(9).

State preservation by repetitive error detection in a superconducting quantum circuit
J. Kelly, R. Barends, A. G. Fowler, A. Megrant, E. Jeffrey, T. C. White, D. Sank, J. Y. Mutus, B. Campbell, Yu Chen, Z. Chen, B. Chiaro, A. Dunsworth, I.-C. Hoi, C. Neill, P. J. J. OMalley, C. Quintana, P. Roushan, A. Vainsencher, J. Wenner, A. N. Cleland & John M. Martinis, Nature 519, 66-69

Quantum computing becomes viable when a quantum state can be protected from environment-induced error. If quantum bits (qubits) are sufficiently reliable, errors are sparse and quantum error correction (QEC)is capable of identifying and correcting them. Adding more qubits improves the preservation of states by guaranteeing that increasingly larger clusters of errors will not cause logical failurea key requirement for large-scale systems. Using QEC to extend the qubit lifetime remains one of the outstanding experimental challenges in quantum computing. Here we report the protection of classical states from environmental bit-flip errors and demonstrate the suppression of these errors with increasing system size. We use a linear array of nine qubits, which is a natural step towards the two-dimensional surface code QEC scheme, and track errors as they occur by repeatedly performing projective quantum non-demolition parity measurements. Relative to a single physical qubit, we reduce the failure rate in retrieving an input state by a factor of 2.7 when using five of our nine qubits and by a factor of 8.5 when using all nine qubits after eight cycles. Additionally, we tomographically verify preservation of the non-classical GreenbergerHorneZeilinger state. The successful suppression of environment-induced errors will motivate further research into the many challenges associated with building a large-scale superconducting quantum computer.