ENTANGLE THIS IV: CHAOS, ORDER AND QUBITS

TITLES AND ABSTRACTS

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Speaker: Vijay Balasubramanian

Title: Quantum Complexity of Time Evolution with Chaotic Hamiltonians

Abstract: We study the quantum complexity of time evolution in large-N chaotic systems, with the SYK model as our main example. This complexity is expected to increase linearly for exponential time prior to saturating at its maximum value, and is related to the length of minimal geodesics on the manifold of unitary operators that act on Hilbert space. Using the Euler-Arnold formalism, we demonstrate that there is always a geodesic between the identity and the time evolution operator e^{−iHt} whose length grows linearly with time. This geodesic is minimal until there is an obstruction to its minimality, after which it can fail to be a minimum either locally or globally. We identify a criterion - the Eigenstate Complexity Hypothesis (ECH) - which bounds the overlap between off-diagonal energy eigenstate projectors and the k-local operators of the theory, and use it to show that the linear geodesic will at least be a local minimum for exponential time. We show numerically that the large-N SYK model (which is chaotic) satisfies ECH and thus has no local obstructions to linear growth of complexity for exponential time, as expected from holographic duality. In contrast, we also study the case with N=2 fermions (which is integrable) and find short-time linear complexity growth followed by oscillations. Our analysis relates complexity to familiar properties of physical theories like their spectra and the structure of energy eigenstates and has implications for the hypothesized computational complexity class separations between PSPACE and BQP/poly and PSPACE and BQSUBEXP/subexp, and the "fast-forwarding" of quantum Hamiltonians.

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Speaker: Maricarmen Bañuls

Title: Entanglement and energy variance

Abstract: Generic eigenstates of non-integrable local Hamiltonians are expected to fulfill an entanglement area law, a necessary condition for their resembling (locally) thermal equilibrium. For arbitrary pure states, which can be written as linear combinations of these eigenstates, we may ask how much entanglement is needed to reduce the energy variance, and how small do we need this to be, in order to have local thermal properties.
We have explored the relation between entanglement and energy variance in a pure state, as the system size increases, for local one dimensional Hamiltonians. Using a systematic construction for matrix product states, we have found that a polynomially increasing bond dimension is enough to

construct states with energy variance that vanishes with the inverse of the logarithm of the system size. Our numerical results suggest that these states, which can be constructed efficiently, do converge to the thermal equilibrium in the thermodynamic limit, while the same is not true if the variance remains constant.

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Speaker: Pasquale Calabrese

Title: Subsystem Trace Distance in Quantum Field Theory

Abstract: I will introduce a recently developed systematic method to calculate the trace distance between two reduced density matrices in 1+1 dimensional quantum field theories. The approach exploits the path integral representation of the reduced density matrices and an ad hoc replica trick. This method is then applied to the calculation of the distance between reduced density matrices of one interval of length ℓ in eigenstates of conformal field theories. When the interval is short, using the operator product expansion of twist operators, a universal form for the leading order in ℓ of the trace distance is obtained. The trace distances among the reduced density matrices of several low lying states in two-dimensional free massless boson and fermion theories are computed and compared with numerical calculations in XX and Ising spin chains.

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Speaker: Jerome Dubail

Title: Operator entanglement: some basic results, and the problem of operator spreading

Abstract: I will start with a brief introduction to "operator entanglement", i.e. the entanglement entropy of operators (viewed as states in the space of operators), and then review a few basic results, including the "operator area law" satisfied by Gibbs states and the "entanglement barrier" faced by the reduced density matrix after a global quench. Then I will turn to the problem of local operators in Heisenberg picture, which spread with time. I will argue that operator entanglement of Heisenberg-picture operators should behave differently in integrable and chaotic systems. I will present rigorous results on this problem for a specific integrable model, the "Rule 54 chain", for which it can be shown that operator entanglement grows logarithmically with time (in contrast to the chaotic case where it is believed to grow linearly).

The talk will be based on joint work with Vincenzo Alba (Amsterdam) and Marko Medenjak (Paris).

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Speaker: Jens Eisert

Title: Holography and matchgate tensor networks

Abstract: The AdS/CFT correspondence conjectures a holographic duality between gravity in a bulk space and a critical quantum field theory on its boundary. Tensor networks - which are briefly introduced in the talk - have come to provide toy models to understand such bulk-boundary correspondences, shedding light on connections between geometry and

entanglement. In this talk, we will introduce a versatile and efficient framework for studying tensor networks, extending previous tools for Gaussian matchgate tensors in 1+1 dimensions [1]. Using regular bulk tilings, we show that the critical Ising theory can be realized on the boundary of both flat and hyperbolic bulk lattices, and explain how critical data can be extracted. Within our framework, we also produce translation-invariant critical states by an efficiently contractible network dual to the multi-scale entanglement renormalization ansatz. Furthermore, we explore the correlation structure of states emerging in holographic quantum error correction.
Using a machinery of holographic Majorana dimer models [2], we are able to compute boundary second moments for arbitrary states within the error correcting subspace. If time allows, we will hint at new connections to questions of complexity [3,4].

[1] Holography and criticality in matchgate tensor networks,
A. Jahn, M. Gluza, F. Pastawski, J. Eisert,
Science Advances 5, eaaw0092 (2019).

[2] Holographic Majorana dimer models of quantum error correction,
A. Jahn, M. Gluza, F. Pastawski, J. Eisert,
arXiv:1905.03268 (2019).

[3] Circuit complexity, entangling power and the linear growth conjecture,
J. Eisert,
in preparation (2019).

[4] Complexity and entanglement for thermofield double states,
S. Chapman, J. Eisert, L. Hackl, M. P. Heller,
R. Jefferson, H. Marrochio, R. C Myers,
SciPost Physics 6, 034 (2019).

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Speaker: Glen Evenbly

Title: Efficient use of tensor networks for tasks in supervised learning

Abstract: Tensor network states, used in the description of quantum many-body systems, share many similarities to the neural networks used in machine learning. As such, many recent research efforts have focused examining the potential application of tensor networks to problems in machine learning such as image classification. However, progress has been limited as traditional tensor network ansatz are often difficult to apply efficiently to machine learning tasks.
In this talk I propose a restricted class of tensor network state, built from number-state preserving tensors, as classifiers for supervised learning tasks. While this restriction limits the type of entanglement that this class of tensor network can produce, they are none-the-less argued as a natural choice for classifiers. Moreover, I describe an optimization algorithm that allows for their efficient training against classical datasets. This proposal is demonstrated using a variety of benchmark classification problems, where number-state preserving versions of commonly used network states (including MPS, TTN and MERA) are trained as effective classifiers.

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Speaker: Hrant Gharibyan

Title: Onset of Random Matrix Behavior in Scrambling Systems

Abstract: The fine grained energy spectrum of quantum chaotic systems, which are widely believed to be characterized by random matrix statistics. A basic scale in these systems is the energy range over which this behavior persists. We defined the corresponding time scale by the time at which the linearly growing ramp region in the spectral form factor begins. We dubbed this ramp time. It is also referred to as the ergodic or Thouless time in the condensed matter physics community. The purpose of my talk is to understand this scale in many-body quantum systems that display strong chaos (such as SYK and spin chain), sometimes referred to as scrambling systems. Using numerical results and analytic estimates for random quantum circuits, I will provide summary of results on scaling of ramp time with system size in the presence/absence of conservation laws.

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Speaker: Cécilia Lancien

Title: Correlation length in random MPS and PEPS

Abstract: The general goal of the work that I will present in this talk is to characterize which features of MPS and PEPS are generic and which are, on the contrary, exceptional. This problem can be rephrased as follows: given an MPS or a PEPS sampled at random, what are the features that it displays with either high or low probability? One property which we will focus on is that of having either rapidly decaying or long-range correlations. In a nutshell, the main result I will state is that translation-invariant MPS and PEPS typically exhibit exponential decay of correlations at a high rate. I will show two distinct ways of getting to this conclusion, depending on the dimensional regime under consideration. Both yield intermediate results which are of independent interest, namely: the parent Hamiltonian and the transfer operator of such MPS and PEPS typically have a large spectral gap.

Based on joint work with David Perez-Garcia, available at arXiv:1906.11682.

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Speaker: Andreas Ludwig

Title: Entanglement transitions

Abstract: We discuss Entanglement Transitions, a novel type of continuous phase transitions. All of the so-far understood continuous phase transitions separate phases with the same entanglement features: (i) Generic Thermal Phase Transitions occurring at a finite critical temperature separate two phases, both of which exhibit Volume Law Entanglement. (ii) Quantum Phase Transitions on the other hand, which occur at zero temperature, separate two phases, both of which exhibit Area Law Entanglement. In contrast, Entanglement Transitions discussed here are continuous phase transitions which separate a phase with Volume Law Entanglement from a phase with Area Law Entanglement. An example of such an Entanglement Transition is provided by the Many-Body Localization Transition which turns out to be of a special type, and is not discussed in this talk. Here we discuss two Entanglement Transitions of a

different type, of a 1D quantum state. (a) The first occurs in a Random Tensor Network driven by varying the Bond Dimension. (b) The second occurs in a unitary quantum circuit in which a local (Haar) random unitary time evolution is disrupted by projective measurements performed at some rate "p" (per unit length). At a critical rate p_c of measurements, the many-body wave function "collapses" to an Area Law entangled state. We show that both transitions, (a) and (b), are described by two (very similar) 2D classical Statistical Mechanics models which possess a critical point in the universality class of a 2D conformal field theory (CFT). The entanglement properties are boundary properties of this 2D CFT. Fine-tuned versions of the transitions, shown to occur for (b) in the limit on infinite on-site Hilbert space dimension, possess a higher symmetry and are described by the CFT of 2D percolation. Upon relaxing the fine-tuning, the resulting reduction of symmetry generates a single, exactly known relevant perturbation of the percolation fixed point, inducing a crossover RG flow to a generic fixed point.

[Work done in collaboration with: Chao-Ming Jian, Andrew Potter, Romain Vasseur, Yi-Zhuang You.]

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Speaker: Kyriakos Papadodimas

Title: Aspects of entanglement and the black hole horizon

Abstract: The holographic correspondence relates black holes to thermal states in strongly coupled quantum field theories. We discuss how the entanglement of simple observables in a QFT in a thermal state allows us to represent the region behind the horizon of the black hole. We discuss how the space-time dynamics near the horizon is related to scrambling and the quantum chaotic nature of out-of-time-order correlators in the dual QFT.

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Speaker: Marcos Rigol

Title: Entanglement entropy of highly excited eigenstates of many-body lattice Hamiltonians

Abstract: The average entanglement entropy of subsystems of random pure states is (nearly) maximal [1]. In this talk, we discuss how the average entanglement entropy of subsystems of highly excited eigenstates of integrable and nonintegrable many-body lattice Hamiltonians (with a conservation law) differ from that of random pure states. For translationally invariant quadratic models (or spin models mappable to them) we prove that, when the subsystem size is not a vanishing fraction of the entire system, the average eigenstate entanglement exhibits a leading volume-law term that is different from that of random pure states [2]. We argue that such a leading term is universal for translationally invariant quadratic models [3]. For the quantum Ising model, we show that the subleading term is constant at the critical field for the quantum phase transition and vanishes otherwise (in the thermodynamic limit); i.e., the critical field can be identified from subleading corrections to the average (over all eigenstates) entanglement entropy [3]. For highly excited eigenstates of a particle-number-conserving quantum chaotic model away from half filling, we find that the deviation from the maximal value grows with the square root of the system's volume, when 1/2 of the system is traced out. Such a deviation is proved to occur in random pure states with a fixed particle number and normally distributed real coefficients [4].

References:
1. D. N. Page, Phys. Rev. Lett. 71, 1291 (1993).
2. L. Vidmar, L. Hackl, E. Bianchi, and M. Rigol. Phys. Rev. Lett. 119, 020601 (2017).
3. L. Vidmar, L. Hackl, E. Bianchi, and M. Rigol. Phys. Rev. Lett. 121, 220602 (2018).
4. L. Vidmar and M. Rigol. Phys. Rev. Lett. 119, 220603 (2017).

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Speaker: Ritam Sinha

Title: Time Evolution of Operator Complexity Beyond Scrambling

Abstract: In fast scramblers, the spread of local information, as diagnosed for instance by OTOCs, proceeds exponentially fast. Local operators grow to the size of the system in times of order log(S), where S is the entropy. On the other hand, randomisation of quantum states in Hilbert space requires the much longer Heisenberg time scale, of order exp(S). We study the evolutions of operator complexity between these two vastly different time scales using the concept of K-complexity. This notion measures operator growth in a specially designed operator basis called the Krylov-basis, which has the advantage of characterising such growth for exponentially long time scales. Using the ETH hypothesis, we argue that the K-complexity in fast scramblers tends to slow down from an exponential to a linear law right after scrambling time. We also characterise how the initially local operator randomises over the operator basis, using the notion of K-entropy, signifying a complete scrambling of the system.

(Work in collaboration with J.L.F. Barbon, E. Rabinovici and R. Shir)

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Speaker: Christoph Sünderhauf

Title: Quantum chaos in the Brownian SYK model with large finite N: OTOCs and tripartite information

Abstract: The Brownian SYK model features all-to-all interactions of Majorana fermions with time-dependent disordered couplings. Quantum chaos and scrambling can be diagnosed with out-of-time ordered correlators (OTOCs) and the tripartite information. After introducing these concepts, I will focus on their computation in the Brownian SYK model.
Exploiting permutational symmetry of averaged quantities leads to a description as an imaginary-time quench problem in terms of bosonic collective modes. Thus, we devise a method to calculate the diagnostics of scrambling within an effective Hilbert space growing merely linearly or quadratically with N. Since this enables us to study large systems up to a million particles numerically exactly, we can explicitly uncover a scrambling time logarithmic in N. Further, we demonstrate the decay to Haar-scrambling values at late times.

The talk is based on our recent work arXiv:1908.00775.

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Speaker: Luca Tagliacozzo

Title: Emergence of universality in the out-of-equilibrium dynamics.

Abstract: I will discuss the appearance of universal features in the dynamic of the transverse field Ising model quenched at and across the quantum critical point.

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Speaker: Tadashi Takayanagi

Title: Entanglement Wedges from Information Metric in Conformal Field Theories

Abstract: We present a new method of deriving the geometry of entanglement wedges in holography directly from conformal field theories (CFTs). We analyze an information metric called the Bures metric of reduced density matrices for locally excited states. This measures distinguishability of states with different points excited. For a subsystem given by an interval, we precisely reproduce the expected entanglement wedge for two dimensional holographic CFTs. The Bures metric is proportional to the AdS metric on a time slice. On the other hand, for free scalar CFTs, we do not find any sharp structures like entanglement wedges. When a subsystem consists of disconnected two intervals we manage to reproduce the expected entanglement wedge from holographic CFTs, with correct phase transitions, up to a very small error, from a quantity alternative to the Bures distance.

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Speaker: Erik Tonni

Title: On entanglement hamiltonians in 1D free lattice models

Abstract: The reduced density matrix of a spatial subsystem can be written as the exponential of the entanglement hamiltonian, hence this operator contains a lot of information about the entanglement of the bipartition. In a harmonic chain and in a chain of free fermions, we present numerical studies concerning the temporal evolution of the entanglement hamiltonians, of the entanglement spectra and of the contours for the entanglement entropy of an interval after a global quench. For a free Dirac fermion on the line and in its ground state, we also discuss the derivation of the CFT expression for entanglement hamiltonian of an interval as the continuum limit of the corresponding lattice results.