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Research Statement

Previous Research Experience

The unifying theme of the research I have performed is the use of quantum entanglement and related information-theoretic quantities as a lens with which I examined problems arising in condensed matter physics and quantum field theory, utilizing concepts and techniques from both disciplines with a combined analytical and numerical approach. While these ideas have been used to analyze a wide range of topics in these fields, the key direction I have explored is the study of non-equilibrium phenomena in many-body systems such as quantum chaos and Floquet physics. In the following paragraphs, I will highlight some of the directions I have worked on. I will then conclude with some future directions I intend to explore.

Quantum Chaos and Information Scrambling

Despite the concerted efforts of theoretical physicists in both the condensed matter and high energy communities, the definition of many-body quantum chaos remains elusive. At present, several diagnostics have been proposed but none are definitive. One promising candidate is the operator entanglement, which is the entanglement entropy of an operator when viewed as a state in the Hilbert space of operators. In a series of papers, I have studied operator entanglement as a measure of quantum information scrambling, thereby providing an alternative route to understanding quantum chaos.

I first began my study of operator entanglement with the operator entanglement of the unitary time evolution operator in two-dimensional conformal field theories (CFT) with the goal of uncovering their scrambling and chaotic behavior. The main quantity used to study quantum chaos is the late-time saturation value of the tri-partite operator mutual information which directly measures the delocalization of quantum information by the time evolution operator. The more negative this quantity is, the greater the degree of scrambling. It was shown that non-chaotic CFTs like the free fermion and compact bosons had little to no information scrambling while the holographic CFTs had maximal information scrambling. We see a further distinction between these theories when we place them in a system with finite size. It was shown that the operator mutual information exhibits quantum revivals for free fermions but not for holographic theories. Curiously, the information scrambling ability of holographic CFTs is reduced by the finite size effect for certain configuration of subsystems. These results firmly established the utility of operator entanglement as a measure of quantum information scrambling.

Beyond conformal field theories, we also looked at information scrambling in disordered condensed matter systems. In particular, we looked at the operator entanglement as well as the out-of-time ordered correlators in disordered condensed matter systems such as the random singlet model as well as a many-body localized spin chain.

I subsequently looked at another measure of quantum correlations known as the logarithmic negativity which only captures quantum correlations as opposed to mutual information which captures both classical and quantum correlations. It was found to also be able to detect information scrambling. The operator entanglement was then refined by looking at the operator entanglement of a local operator. A local operator in the Heisenberg picture can be viewed as a forward time evolution followed by a localized perturbation with an eventual backward time evolution, allowing for a direct interpretation in terms of the butterfly effect in chaotic systems. The local operator entanglement is shown to be able to clearly distinguish between integrable and chaotic systems.

Inhomogeneous Quenches, Quantum State Preparation and Genuine Tripartite Entanglement

More recently, I have turned my attention to the study of quantum dynamics in inhomogeneous systems. In a series of works, I have looked at the dynamics of quantum information under unitary time evolution by spatially inhomogeneous Hamiltonians. Given a translationally invariant many-body Hamiltonian that can be decomposed into a sum of local terms, a spatially inhomogeneous Hamiltonian can be produced by changing the weight of each local term. Put differently, the sum of local Hamiltonians over spatial sites can be modulated by a spatially inhomogeneous envelope function. With a judicious choice of an envelope function, the spatially inhomogeneous Hamiltonian can produce novel dynamics of quantum information. In this construction, we have a family of spatially inhomogeneous Hamiltonians that interpolate between the uniform Hamiltonian and what is known as the sine-squared deformed (SSD) Hamiltonian where the envelope function is a simple sine-squared function. This is a particular spatially dependent deformation of the Hamiltonian with a particular point at which the resulting Hamiltonian density vanishes.

We begin this line of research by investigating the quenches of the thermal Gibbs state by these inhomogeneous Hamiltonians. It was shown that away from this special point where the Hamiltonian density vanishes, the thermal state cools into the vacuum state under a quench by this SSD Hamiltonian and the resulting entanglement entropy is that of the vacuum state. On the other hand, the entanglement entropy of subsystems that contain this special point approaches the thermal entropy of the total system. Therefore, all the information has been concentrated at this special point, coalescing into a black hole-like excitation.

Making a connection to my previous work on operator entanglement and quantum chaos, the information scrambling properties of these inhomogeneous Hamiltonians was considered. While the free fermions exhibited no information scrambling as expected, it was found that the spatial inhomogeneity reduced the information scrambling properties of the holographic CFTs. Furthermore, time evolution under the SSD Hamiltonian in holographic CFTs produced genuine tripartite entanglement in the sense that three spatially separated subsystems can share correlations that are not shared between any two of these subsystems. This pattern of entanglement is novel and it would be interesting to look for such instances of multipartite entanglement in other many-body systems.

Since then, we have also looked at the dynamics of information after a quench of a lowly entangled state, namely the conformal boundary state, as well as a locally excited state. The boundary states in conformal field theory possess little spatial entanglement and are the analogs of product states in conformal field theory. Just as in the quench of the thermal state, quenches of these lowly entangled states by the spatially inhomogeneous SSD Hamiltonian produces the vacuum state away from the special fixed point. Lastly, we also considered inhomogeneous quenches of locally excited states. This local excitation produces a bell-pair of quasiparticles. Whenever one but not both of the quasiparticles is inside of the subsystem A, the entanglement entropy increases from the initial vacuum value. Ordinarily, these quasiparticles would move with the speed of light but since the Hamiltonian is inhomogeneous, they move with a spatially-inhomogeneous speed given by the envelope function of the Hamiltonian.

Future Directions

The interdisciplinary research I have carried out so far has opened a myriad of interesting avenues for further research. The main direction I hope to pursue in my future research is the application of quantum information concepts to the study of many-body physics and field theory. It would be fruitful to continue exploring the two main research directions I am currently working on, namely the study of entanglement dynamics in inhomogeneous systems as well the characterization of many-body quantum chaos.

Dynamics in quantum circuits

While a big portion of my research involves studying the dynamics of quantum information in infinite-dimensional systems, some of these phenomena can be realized in finite dimensional systems which allow for certain questions to be formulated more rigorously. For example, the dynamics of entanglement in holographic conformal field theories are described by entanglement membranes which can show up in Haar-random unitary circuits. I am particularly interested in certain kinds of exactly solvable unitary circuits known as dual-unitary circuits that are generically quantum chaotic. These circuits are special because they are the only circuits with maximal entanglement velocity. The analytical tractability of these models allowed for a variety of physical quantities to be computed such as correlation functions, entanglement entropy and the spectral form factor. Despite the tremendous strides made in understanding dual-unitary circuits, several foundational questions remain unanswered. Perhaps the most glaring gap in our knowledge of dual-unitary circuits are the correlation functions between two operators that do not only act on single sites or a cluster of contiguous sites. It is known that the correlation between two single-site operator is non-zero when one operator sits on the edge of the lightcone of the other. For general choices of operators of arbitrary supports and locations, which correlators vanish and which don't? Are some of these correlators dominant? Can we also develop a hydrodynamic picture for operator spreading as was done for random unitary circuits? Answering some or all of these questions will give us a deeper understanding of the dynamics of operator spreading in dual-unitary circuits which thus far has been limited to only single-site operators.

There are several variants of these circuits that are still not well-explored. For example, it is possible to consider dual-unitary circuits that conserve charges. The conservation of charge is known to modify the dynamical properties of Haar-random unitary circuits. A recent paper studying the entanglement entropy of disjoint intervals in dual-unitary circuits showed that introducing charge conservation causes these dual-unitary circuits to behave more like integrable models. It is therefore natural to consider how charge conservation in these circuits will affect various quantities such as the tripartite information and symmetry-resolved entanglement.

Quantum Advantage

Perhaps one of the biggest challenges in physics in the early twenty-first century is demonstrating that quantum computers can outperform classical ones in certain tasks. This challenge, known as quantum advantage, is key to sustaining interest in quantum computing, which is still in its early developmental stages, from the scientific community and the broader society. Developments in this field hold the potential to radically transform a plethora of fields ranging from materials and pharmaceutical research to information security, leading to lasting impacts in society beyond science. At present, almost all demonstrations of quantum advantage rely on mathematically contrived problems instead of physically motivated ones. It remains to be seen if further demonstrations of quantum advantage can be accomplished using physically relevant problems. With the rapid pace of developments of near term quantum computers, also known as noisy intermediate-scale quantum (NISQ) devices, several research teams, including Google, IBM and Quantinuum, are racing to reach this milestone. I am currently exploring certain quantities and processes in finite size quantum circuits that are likely to be difficult to simulate on classical computers and yet have signals that are sufficiently large to be measureable on a quantum computer, thereby providing a possible avenue for demonstating quantum advantage.

Conclusion

The field of non-equilibrium many-body physics is an active area of ongoing investigation by a large community of condensed matter physicists with potential ramifcations for near-term quantum computing devices. This source of open questions will allow me to come up with a productive, long-term research program and I believe your physics department will be a great place for me to carry out this research.

Furthermore, many of these condensed matter problems can be studied both analytically and numerically with a solid understanding of non-relativistic quantum mechanics. Students could, for example, implement models of chaotic spin chains, calculate entanglement measures, or run small-scale simulations on publicly available quantum computing platforms. These projects are tractable, yet open-ended enough to yield new insights, and have the potential to lead to co-authored publications in peer-reviewed journals.