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Controlling Quantum Information by Quantum Correlations

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Abstract

The report describes hypotheses, aims, methods and results of the project 20170675PRD2, "Controlling Quantum Information by Quantum Correlations", which has been run from July 31, 2017 to January 7, 2018. The technical work has been performed by Director's Fellow Davide Girolami of the T-4 Division, Physics of Condensed Matter and Complex Systems, under the supervision of Wojciech Zurek (T-4), Lukasz Cincio (T-4), and Marcus Daniels (CCS-7). The project ended as Davide Girolami has been converted to J. R. Oppenheimer Fellow to work on the project 20180702PRD1, "Optimal Control of Quantum Machines", started on January 8, 2018.

Background and Research Objectives

Intelligent agents aim at controlling Nature to perform tasks. While macroscopic objects are relatively easy to manipulate, quantum systems, as atoms and photons, demand exquisite techniques. A controller acquires information about a system via measurements. Then, it drives the system towards a target configuration by applying a feedback, e.g. exerting a force. Such interactions usually destroy the fragile properties of a quantum system. When the controller itself is a quantum device, it can establish quantum correlations with the system of interest. A greater amount of information then flows between them, without damaging the system properties. Yet, it is unknown whether quantum correlations may control a device running a real-world quantum computation, because uncontrollable error sources perturb the system and the controller. Dr. Girolami has recently developed methods to identify and calculate quantum correlations which are noise resilient, proposing and testing efficient experimental strategies to detect them. Also, he has showed how such correlations enable to build measurement devices whose precision is unmatched by classical apparatuses.

The goal of the project was to achieve optimal control of quantum systems in realistic conditions, outperforming the best classical strategies. The first objective was to use noise immune quantum correlations to minimize the consumption of precious experimental resources in quantum system engineering. In practice, every process is thermodynamically irreversible. The investigator planned to employ quantum correlations to minimize the energy dissipated when driving a quantum system into a desired state. He would have then investigated how they help to achieve energy efficient control of Hamiltonian dynamics, where the objective is to implement a given quantum operation. The result should be applied to improve the control of important quantum processes in noisy environments: logic gate quantum computations, ideal for number factoring; quantum annealing, the alternative computation paradigm implemented in the D-Wave "chip", which excels in optimizations; sensing protocols, where peculiarly sensitive quantum probes extract information about otherwise unmeasurable physical quantities. The investigator was expected to design experimental demonstrations of optimal quantum control, implementable in cold atom experiments. A puzzling problem is to make quantum control scalable. That is, being

applicable even to aggregates of millions of qubits, requiring resources scaling linearly with the size of the system. He planned to show how intra-system quantum correlations speed-up distribution of information in quantum networks. A large many-body system will be governed by manipulating only few sites, and using correlations to quickly spread the controller instruction to the whole system. The project outputs was anticipated to be of immediate use at LANL, which is currently investing its unique blend of expertise in quantum information and condensed matter physics to explore the capabilities of the D-Wave machine, the world's largest quantum computer, and to engineer interferometers of unprecedented sensitivity by controlling Bose-Einstein condensates.
The project fully aligned with the LANL commitment to be a strong player in developing quantum physics and technologies. This is one of the most active field of modern science, which has been identified as a strategic priority by the National Science and Technology Council and the NSA, and attracting investments from innovation champions as Google, Microsoft, IBM, and D-Wave. Achieving full control of many body quantum systems will pave the way to implement large scale, robust quantum computers, sensors and simulators. Such device are expected to dramatically change the way we process data, solving computational problems beyond the capability of the best classical machines, and leading to innovative solutions in critical sectors as environmental sustainability, healthcare, energy provision, and national security.

Scientific Approach and Results

The work performed during the project concerned two main research lines:

1) Description of correlation structures in multipartite quantum systems
2) Quantification of dynamical sensitivity of quantum systems by employing methods of information geometry

An account of the performed research follows in the next two sections.

1) Description of correlation structures in multipartite quantum systems

The first part of the project was essentially a continuation of Dr. Girolami recent work on the characterization of genuine multipartite correlations in many-body systems [1]. It was performed in partnership with Prof. C. Susa of University of Cordoba, Colombia, a long-term collaborator of Dr. Girolami. The results of the study has been published in Ref. [2].

Correlations, capturing statistical relations between measurements performed at different times, or at different sites, take centre stage in many disciplines, as they often unveil dynamical and structural properties of complex systems. Yet, while bipartite correlations can be assumed to be well understood both in the classical and quantum scenarios, multipartite correlations are still somehow *terra incognita*, due to the daunting number of degrees of freedom that are necessary to describe systems of many particles. While correlation functions, e.g. covariances, capture linear correlations between variables, the investigator here considered correlation measures to be more general descriptors of the information about joint properties of composite systems. Correlation patterns, the amount of correlations of different orders (tripartite, four-partite, and so on), describe collective properties of many-body systems, as demonstrated in recent theoretical works, and also verified experimentally [3-7]. Recently, Dr. Girolami and colleagues proposed a framework to describe *genuine* multipartite correlations for quantum and classical systems, providing a method to compute without ambiguities correlations of order in an N-particle system. As states encoding the same amount of information can display very different correlation patterns, he introduced an index to classify them, called weaving. Genuine multipartite correlations express how a many-body system is different from the sum of its parts independently investigated, while weaving captures how such difference scales with the size of the considered parts.

In this project, closed formulas of both genuine multipartite correlations and weaving, as measured by the von Neumann relative entropy, have been derived for the N-qubit GHZ (Greenberger–Horne–Zeilinger) state mixed with white noise [8], a configuration of high relevance for quantum information processing [9]. For such states, a comparison between weaving and the quantized neural complexity has been run [10], being the latter a measure which has been employed to characterize correlation patterns in classical neural networks.

To summarize, a full-fledged characterization of genuine multipartite *quantum* correlations, including entanglement and other kinds of correlations, after promising initial steps, may be achieved by adapting the framework here proposed. Second, the results pave the way for investigating the intriguing notion of genuine multipartite temporal correlations, and therefore the complexity of a process, where the correlations are computed between the state of the system at different times. This promises to be an appealing strategy to characterize memory effects in classical and quantum dynamics. A further line of investigation concerns the experimental detection of quantum complexity without state reconstruction. On this hand, the entropic measure of weaving may be estimated by polynomials of state purities, i.e. trace of squared density matrices and their higher powers. This could be achieved by generalizing the quantitative bounds to the relative entropy of coherence and coherent information in terms of such functionals. It is well known that local purities are observables, e.g. via Bell state measurements.

2) ***Quantification of dynamical sensitivity of quantum systems by employing methods of information geometry***

In the second part of the project, Dr. Girolami identified a design principle of optimal quantum state engineering. He computed the expression of the best (fastest) quantum operation which transforms a given input state in a desired output even in the presence of noise. The method is hardware independent. It can be tested in laboratory with current technology in a number of standard testbeds, e.g. ion traps and photonic systems.

Quantum systems can outperform classical devices in computation and information processing protocols [9]. A key factor determining a device efficiency is how fast it responds to an instruction, encoded in the physical implementation of a logic gate or a communication channel. Yet, a system is also sensitive to the perturbation of error sources, which are detrimental to its performance. The investigator conceived a method to discriminate between quantum and classical effects that induce a dynamical change in the state of a system, when a quantum operation is performed. He defined the sensitivity to the former as the quantum skew information of the system state. He found a use for such concept, proposing a geometric design principle for optimal quantum state driving, the task of preparing a quantum system in a target state by employing one of a determined set of available quantum operations. The best driving strategy is the input/output path which requires the minimum quantum skew information. He also identified the expression of the best (fastest) quantum operation which transforms a given input state in a desired output in the presence of noise. The result is applicable for example, to the preparation of a spin polarization from an initial right state to a final left state, while disturbed by interactions with an optical cavity [11]. State preparation is a necessary step in any quantum computation, thus the scope of the result appears broad. The method is hardware independent, as it works for any physical setup (ion, photons, etc). It can be tested in laboratory with current technology in a number of standard scenarios, e.g. ion traps and photonic systems.

The result sheds light on the usefulness of geometric methods to establish the fundamental limits to quantum information processing. It also appears the ideal framework to reach such limits, posing and solving critical problems as determining energy and time efficient strategies to control quantum systems.
Dr. Girolami is currently writing up a paper where the technical derivation of the results is reported and discussed in relation to physical settigns of experimental interest. The manuscript will be submitted to the premier physics journal Physical Review Letters.

Anticipated Impact on Mission

Tie of project results to mission

The project aligned with the LANL missions of advancing information technology and basic understanding of materials. The project tackles the fundamental problem of describing the physics of many-body quantum systems, the hardware of future quantum computers, simulators, sensors, and communication protocols. On this hand, new measures of quantum information will advance the understanding of correlation structures in complex quantum systems. The project also planted the seeds to address issues emerging in the soon expected transition from proof-of-concept to industry scale quantum processes. New design principles of quantum control will assist technologists in upsizing and upgrading current quantum machines. The ability to speed-up searches in unstructured data will exponentially decrease the time taken to study complex systems via computer simulations. This will hugely impact the economies where information technology plays a key role, and accelerate the discovery of new inherently quantum materials and their applicability for industry. Replacing classical devices with superior quantum gadgets will also contribute to environmental sustainability. For example, optimal control of quantum devices will enable to build more sensitive heat and mass detectors, employable to survey for oil, gas, metals, and seismic activity. Relying on quantum computers for elaborating data, the need for environmentally traumatic geophysics explorations will be reduced. Moreover, optical control of quantum pattern recognition and imaging devices will allow for employing them as diagnostic tools in biomedical research and industrial quality control.

Summary of activities to accelerate and maximize the project impact

The following activities were planned and performed in order to ensure the transition of project capabilities:

- Davide Girolami has met with his mentors weekly to evaluate the project progress and discuss future research directions.
- He has delivered seminars during group meetings (Quantum Lunch seminar series and informal meetings), published drafts and manuscripts. Those materials has detailed his technical work and allowed for evaluation from the physics community. He will also present the project results on premier scientific conferences in the next months (20th SQuInT Workshop, APS March Meeting 2018).
- He will be involved in writing future grant proposals based on his work.

Conclusion

The compact expressions of complexity measures make them interesting tools to investigate multipartite correlation patterns, which are carriers of information about key properties of many-body systems. The project produced a comparative study of weaving and neural complexity for correlated symmetric quantum states subject to a white noise channel. New lines of research are expected to emerge from the interplay between information theory and complexity science concepts. The second project output concerned the application of information-geometric methods to quantum system engineering. A measure of state sensitivity to general quantum dynamics has been derived. A design principle of optimal quantum control of complex systems has been then conceived.

The project results have allowed a swift kick-off of the follow-up project “Optimal Control of Quantum Machines”, which is expected to coherently share the most of research methods here reported. It is indeed anticipated that Dr. Girolami will continue to work towards delivering strategies to efficiently control quantum systems.

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