Complex quantum systems for machine learning

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In the last decades, Complex Systems have been explored in physical systems also in the quantum regime, with enormous advances both in their theoretical treatment as well as in the ability to detect and manipulate individual quantum objects and couple them under control. Experiments involving complex quantum systems are realized with ions, cold atoms, superconducting circuits, and optical modes, to mention some. Fundamental open questions in this context range from the characterization of novel regimes, like e.g. many-body localization, to the emergence of collective phenomena, like time crystals, to the effects of coherences and many-body correlations, with no classical analog, in processing information. Beyond the theoretical challenges in understanding Complex Quantum Systems, these are crucial also in many applications such as quantum computing, the quantum Internet, or quantum simulations. In this talk I will present some results on the use of complex quantum systems for machine learning purposes.

Non-conventional computing inspired by the brain, (classical) neuromorphic computing, is at present successful approach in a broad spectrum of applications, also burgeoning due to big data availability. Within this context, recently neuromorphic approaches have been proposed also in quantum substrates as non-conventional, mostly analog, forms of machine learning. In this talk we are going to present Quantum Reservoir Computing. The classical version of this approach has been developped in the last 20 years. The idea in a nutshell is to process an input injected into a (complex) physical system and to optimize only the output layer for a certain task, with a considerable advantage with respect to deep neural network settings. Several classical systems have been considered as classical reservoirs ranging from optical, to mechanical or even biological implementations [1]. Moving from classical to quantum physical reservoirs, however, opens a series of new challenging questions, related to fundamental as well as realization aspects. Examples are the identification of the best quantum regimes of operation, the role of statistics, or of quantum coherences and entanglement. Indeed quantum reservoir computing has the potential to remarkably boost the processing performance in temporal tasks by exploiting quantum coherences, not requiring error correction, and it is suited for fully quantum information processing (with quantum inputs).

After introducing the Quantum Reservoir Computing and showing how memory and non-linearity arise in a quantum formalism, we will discuss the crucial aspect of quantum measurement in the online series processing and propose a solution based on weak measurment [2].

The use of complex (quantum) systems as reservoirs is strongly influenced by their operation regimes, as we will discuss in the context of dynamical phase transitions [3]. A common setting is based on a qubits network (Ising model in transverse field) as a reservoir. This exhibits phenomena like many-body localization or thermalization, which influence the spread and processing of information. Looking at reservoir in these dynamical phases, we establish that the thermal phase is naturally adapted to the requirements of quantum reservoir computing and report an increased performance at the thermalization transition.

Another aspect we will present is the possibility to perform reservoir computing with quantum fluctuations of light, considering Gaussian states of continuous-variable in a photonic network. While these quantum states are insufficient for universal quantum computing, they are nevertheless enough for universal reservoir computing. Tunable nonlinearity is achieved through the injection of the input quantum state [4]. Finally, to address non-trivial temporal tasks, we propose a photonic platform suitable for real-time quantum reservoir computing, and address the effect of statistical noise [5].

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