From many-body to many-time physics

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Quantum (multi-time) correlations in time have a surprisingly similar structure as spatial quantum (many-body) correlations, formally related via the Choi-Jamiolkowski isomorphism [1]. As a consequence multi-time processes are endowed with the same richness as many-body physics, including temporal entanglement and well-defined causal structures. We dub this as *many-time physics* and consider both the contexts of naturally noisy near-term device dynamics and more general non-Markovian open quantum systems.

Recently, we have developed a generalised version of quantum process tomography to characterise arbitrary non-Markovian processes in practice [2,3]. By probing a system with structured sequences of operations, and measuring its response, this procedure estimates the process tensor representation of the dynamics across some number of times. The resulting characterisation contains all information about the multi-time correlations, and carries straightforward interpretations that can be brought across from many-body physics.

Building off of this, we develop a family of tools that permit us flexible access to many-time physics on quantum information processors, which are then demonstrated on IBM Quantum devices [4]. These tools take into consideration the available device control, and extract various properties of a process given those constraints. The level of control includes, for example, the case of unitary-only manipulations of a state, as well as showing how to bootstrap the design and implementation of probabilistic quantum channels for complete characterisation.

At first, we use this to access short-range microscopic properties, such as the witnessing of genuine multi-time entanglement and measuring estimators for non-Markovian memory. Then by generalising classical shadow tomography we access macroscopic features such as long-range correlation functions and the marginal processes across different time scales. Finally, we develop and demonstrate different methods to efficiently estimate both temporal and spatiotemporal tensor network representations of the process itself – for both the study and control of complex dynamics. Our results demonstrate how to access and learn the many-time phenomena exhibited by non-Markovian open quantum systems from the coarse context of near-term quantum sensors all the way up to fault tolerant quantum simulation. These techniques are pertinent to generic quantum stochastic dynamical processes, with a scope ranging across condensed matter physics, quantum biology, and in-depth diagnostics of NISQ era quantum devices.

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