Switching quantum memory on and off

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PERSPECTIVE

Switching quantum memory on and off

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Abstract

Modifying the Markovian (memoryless) or non-Markovian (memory-keeping) nature of the environment-induced evolution of an open quantum system is crucial in quantum information theory, because it is linked to quantum memory control. A recent work (Brito and Werlang 2015 *New J. Phys.* **17** 072001) shows that such a goal can be achieved without operating on unaccessible environmental features. In fact, transitions between Markovian and non-Markovian regimes of a qubit dynamics can be induced on demand if the qubit is coupled to a controlled auxiliary system. This is a step towards the improvement of quantum devices, aiming at exploiting dynamical memory effects by an external control.

The possibility of controlling the memory capacity of our brain when required would be a quite intriguing feature for human life. In fact, such an achievement would enable sentences like: 'I do not want to keep a memory of the unhappy moment I am living, so, please, turn my memory off!' or 'I really desire to never forget this wonderful experience: it is just the time to switch my memory on and enhance it!'. However, this possibility seems too far away to be reached in the ordinary life of macroscopic organisms like human brains. Differently and interestingly, this is not the case for microscopic objects living in the quantum world.

Nowadays quantum technology is based on the exploitation of peculiar resources, like quantum coherence and quantum correlations, which permit quantum information and computation processing [1]. However, the maintenance of these quantum resources is hindered by the detrimental role of the environment surrounding the open quantum system [2]. The research of strategies to protect and control quantum resources has therefore become central in the scientific community [3, 4]. In this context, the use of non-Markovian and suitably engineered environments has been particularly useful [5–10]. In the theory of open quantum systems, one usually names as Markovian those environments which induce a memoryless dynamics of the quantum system with which they are interacting: the state of the system at time t is determined by the state of the system at time $t - \mathrm{d}t$, schematically $\rho(t - \mathrm{d}t) \to \rho(t)$. This behavior usually happens when the environment correlation time τ_E is shorter than the typical system lifetime τ_S. Nevertheless, it can happen that the environment has a τ_E larger than τ_S and is thus able to keep a memory of the quantum coherence of the system. Under such conditions the environment is called non-Markovian and induces a memory-keeping dynamics such that the state of the system at time t is affected by all its past history, starting at time t_0, that is, $\rho(t_0) \to \rho(t)$. Usually, these dynamical conditions are due to intrinsic unaccessible characteristics of the environment. For instance, in the paradigmatic situation of a qubit (two-level system) embedded in a cavity, the qubit dynamics will be Markovian or non-Markovian, depending on the quality factor Q of the cavity: high values of Q reduce the spectral density bandwidth and therefore increase the correlation time of the cavity itself [2], but these values are unadjustable during an experiment. In order to conveniently investigate the influence of the environmental traits on the dynamics of a quantum system and to exploit quantum memory effects, it is desirable to design appropriate structured environments where the parameters ruling the system evolution are experimentally accessible.

The work of Brito and Werlang [11] addresses this issue by supplying a composite model where the dynamical character (Markovian or non-Markovian) of a subsystem of interest, a qubit, can be changed *on demand* if it is coupled to a controlled auxiliary system, another qubit. Both qubits interact with a common bosonic reservoir at thermal equilibrium. This insightful idea relies on considering the qubit of interest q_S as

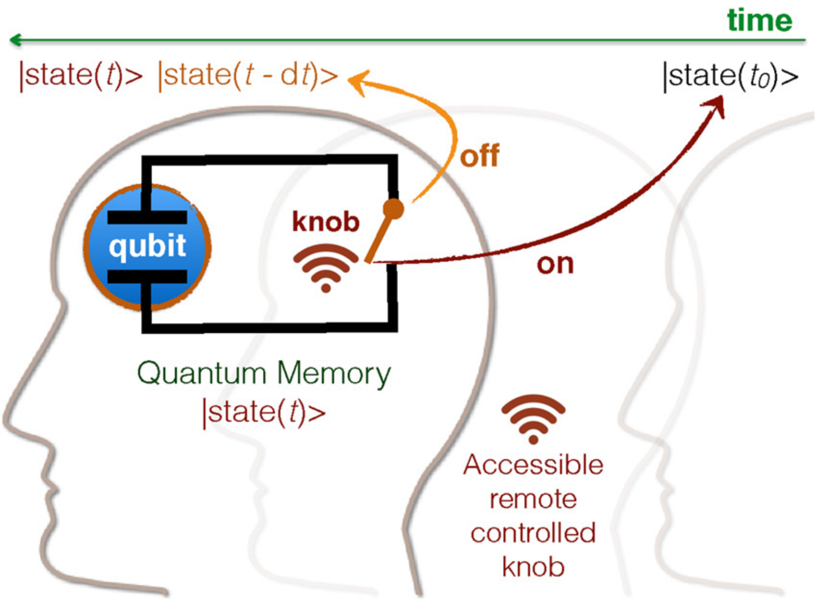

Figure 1. Sketch of a quantum memory knob. The quantum bit (qubit) is a two-level system playing the role of an elementary quantum memory. A composite engineered environment, made of an auxiliary two-level system and a bosonic reservoir at thermal equilibrium, acts as a control circuit that is able to dynamically turn off and on the memory (non-Markovianity) of the qubit dynamics by a knob, depending only on accessible parameters. If the knob is switched off, the dynamics is memoryless (Markovian), and the qubit state at time t, $|\mathrm{state}(t)\rangle$, only depends on the state at the very short time before $t - \mathrm{d}t$, $|\mathrm{state}(t - \mathrm{d}t)\rangle$; if the knob is switched on, instead, the dynamics is memory-keeping (non-Markovian), and the qubit state at time t depends on all its past history starting at t_0, $|\mathrm{state}(t_0)\rangle$, when the circuit was closed (switch on).

affected by a structured environment $\mathcal{E}$, consisting of the auxiliary qubit q_A plus the bosonic reservoir $\mathcal{R}$, which acts as an effective environment for the qubit. The dynamics of q_S is standardly retrieved by tracing out the degrees of freedom of q_A and $\mathcal{R}$. Due to the experimental accessibility of q_A, the control of the non-Markovianity of q_S can be simply realized by tunable features of the two-qubit subsystem alone, like initial state and coupling strength. This way, the manipulation of unaccessible properties of the reservoir $\mathcal{R}$ is avoided. This system demonstrates the existence of an *in situ* knob, which allows for dynamically varying the behavior of a quantum system evolution, as illustrated in figure 1. The presence of the auxiliary qubit q_A not only has quantitative effects on the dynamics of the qubit of interest q_S but may also have a determinant impact on its qualitative nature.

This work highlights the possibility that suitably engineering the coupling with an auxiliary qubit, which is part of a compound environment, can efficiently harness the quantum memory stored in a target qubit. Such an approach also appears to be more straightforward and flexible than those requiring initial preparation of correlated environmental states [12, 13], and, since it takes into account the temperature of the reservoir, provides other clues with respect to recent proposals at zero temperature [14]. Solid-state devices, like the ones based on circuit quantum electrodynamics [15], can take advantage of these characteristics that make the proposed system feasible within this experimental framework.

The outlook of the work by Brito and Werlang [11] is both technological and conceptual. Regarding the technological viewpoint, the reported results could help to improve quantum devices in order that the feature of possessing either a Markovian or a non-Markovian evolution can be maximally exploited. Some studies have shown that the efficiency of energy transport in the photosynthetic system could be enhanced in the presence of a non-Markovian environment [16, 17]. In this sense, the control of the non-Markovianity could be utilized for developing quantum machines analogous to biological systems. There are, finally, some conceptual aspects opened by the work [11]:

(i) The typical encountered quantum evolutions are either Markovian or non-Markovian from the beginning. It remains to understand what is the meaning and the effect of 'changing in time', by a knob, the dynamical behavior of a quantum system.

(ii) The previous problem then leads one to ask for the possible existence of a minimal timescale after which it is possible to observe the effects of non-Markovianity in the evolution.

(iii) The proposed engineered environment is such that there may occur situations where the dynamical map of the qubit of interest, q_S, is not linear, since it depends on the initial state of q_S itself. In these special cases, it is not clear whether it is meaningful to speak about Markovianity and if current non-Markovianity measures [18–21] can be employed.

(iv) As a multidisciplinary perspective, the possibility of dynamically changing in principle the memory capability of a quantum system evolution enables the question of whether dynamical systems in Nature may assume such a behavior by self-adjusting in order to inhibit or foster a given process.

These issues pave the way to further investigations in the near future.

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