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Multi-time quantum process tomography–and beyond–on superconducting qubits

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All current quantum devices suffer from noise originating from system-environment interactions. Often the noise is non-Markovian, i.e. correlated across the time-steps of a quantum circuit—as reported in spin silicon platforms and the superconducting devices of IBM and Google. However, most characterisation techniques assume Markovian (uncorrelated) noise, which results in inaccurate gate fidelities and increased error rates.

Non-Markovian noise can arise from classical sources (temperature, electronic noise, etc.), or quantum sources (a nearby quantum system that mediates the correlations). Existing theoretical approaches typically only access two-time correlations (dynamical maps), while experimental mitigation strategies have been ad hoc, lacking a rigorous, general framework.

The process matrix formalism provides such a framework, encoding all multi-time correlations of a quantum process, allowing us to quantify the strength and nature of non-Markovian noise. Although this method has been used in various experiments, full process matrix reconstruction has remained out of reach because it was believed to require mid-circuit measurements with rapid feed-forward capabilities unavailable in current devices—leading only to partial characterisations.

Here, we present the first complete tomography of a multi-time quantum process on a superconducting qubit, providing a full description of its non-Markovian noise. We achieve this using mid-circuit measurements combined with a post-processing trick that avoids the need for a feed-forward mechanism. Our experiments use devices from the University of Queensland and IBM Quantum's cloud platform. We measure both general and quantum non-Markovian noise and construct a theoretical model to compare with our results. We also present several pathways to utilise this method for real impact on quantum devices, combining MPOs and AI to reduce the computational and experimental data overhead and the needs of experimentalists to achieve their goals. Our methods enable rigorous characterisation of non-Markovian noise, advancing our understanding and opening pathways to more effective noise mitigation.

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