A Quantum Memory Witness Protocol for Benchmarking Nonclassical Behavior in Quantum Processors

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Quantum computers promise computational advantages beyond classical limits. Although reported gate fidelities are high for modern devices, widely thought to indicate high performance, they do not guarantee the preservation of nonclassical behavior at scale and fail to provide a holistic measure of a quantum device's performance under extended entanglement and circuit depth. In this work, I design a framework that embeds a theoretical quantum witness of non-Markovianity within circuits to establish a depth-dependent, scalable, and architecture-agnostic benchmark of quantum memory retention. The witness, introduced in prior literature, combines Pauli-X and Pauli-Z correlators with an identity debiasing term, such that a negative witness score can only be produced by quantum memory. In this work, I produced individual correlator circuits and a maximally entangling base circuit using AWS Braket, in the native gate sets of various quantum devices. Correlating the resulting witness scores with circuit depth, I discovered a novel 'Critical Depth' metric which characterizes the maximum entanglement depth at which a quantum computer retains nonclassical properties (after which noise effects induce decoherence in both X and Z bases). Such analysis additionally quantifies the rate of decoherence. Preliminary results across multiple hardware systems indicate that despite strong single- and two-qubit fidelities, current quantum devices fail to retain quantum memory within one to two entangling layers, with fidelities beyond 0.99 being required for exceeding these depths. The proposed methodology is scalable across differing computing architectures and is intrinsically holistic.

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