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Characterizing quantum devices using model selection

Robin Blume-Kohout, PI
Travis Scholten

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Quantum information processors are a new kind of computing device with the potential to solve certain problems very quickly. The quantum bits, or "qubits," that enable such processors are being developed at Sandia and around the world. In support of this effort, Sandia's Center for Computing Research is designing methods and algorithms to characterize and debug the behavior of experimental qubits, such as trapped ions and electron spins in silicon.

This is a challenge, because qubits are hard to characterize for exactly the same reason that they are powerful. Their behavior (and misbehavior) is far richer and more complicated than that of classical bits! The most reliable models of quantum errors have infinitely many parameters, and we never have enough data to fit all of them. Until now, researchers simply threw out most of these parameters resulting in a crude approximation that makes the problem tractable, but isn't reliable or accurate enough for Sandia's experimental work.

Our new techniques use statistical model selection to identify "significant" error parameters on the fly, applying a data-driven *information criterion* to choose a Hilbert space that describes the data well without overfitting. To find a reliable criterion, we needed to evaluate many candidates on an enormous corpus of test cases–for which we relied on Red Sky's ability to run parallel Monte Carlo simulations. Our computations demonstrate how classic model selection methods have to be modified for quantum devices. These results will enable new techniques that identify the effective dimension of as-built qubits on the fly, and then use this information to reliably pin down error behaviors and produce successively better and more useful qubits.

This project highlights the close and productive relationship between Sandia and the University of New Mexico, where Travis Scholten is working towards a Ph.D. in physics. Both the intellectual environment of UNM and the high-powered supercomputing available at Sandia were critical ingredients in achieving our research goals.

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Video Caption:
The goal of quantum heterodyne tomography is to deduce the quantum state of a laser beam (or "optical mode") by repeatedly measuring its field quadratures. This video shows how our best estimate evolves as we take more data (from 1 to 1000 samples). What's unique about our algorithm is its ability to choose a model for the data on the fly, and thus to avoid overfitting. In this simulation, the true

quantum state is 5-dimensional, and our algorithm's running guess is shown by the gray bar. As more data comes in, the algorithm converges to the correct dimension *without* knowing it in advance. More importantly, by choosing a model wisely, our algorithm can reliably estimate the quantum state with very high accuracy, as shown by the green bar labeled "Fidelity."

Quote:
Monte Carlo simulations on Red Sky allowed us to explore the enormous space of test cases for our algorithm, and thus to figure out how model selection could enhance quantum tomography. ~Travis Scholten