Application Motivated Benchmarking of Quantum Computation and Compilation

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Motivation

By benchmarking NISQ technology, great progress can be made towards building large scale universal quantum computers.

What: Noisy Intermediate Scale Quantum computers are built from of the order of 50-100 qubits. This is enough to perform interesting computations, but not to also allow fault tolerance.

Why: While allowing us to begin to explore interesting applications of quantum technology, NISQ devices also provide insights into the design and utility of universal quantum computers.

How: Benchmarking NISQ devices reveals the technological innovations required to construct more powerful devices by demonstrating the approaches that are most beneficial.

We keep two benchmark design philosophies in mind:

- Incorporate the full stack, including the compiler. This extracts all information about how best to exploit NISQ technology.
- Complement traditional benchmarks with others motivated by applications to measure the device's areas of applicability.

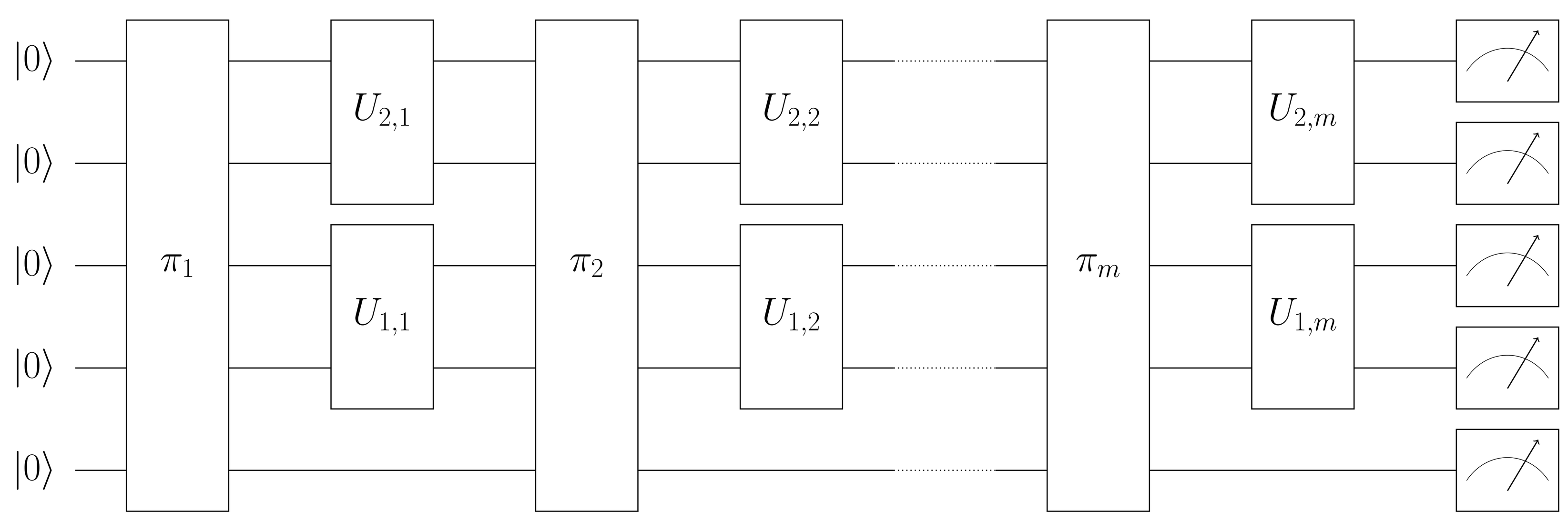
We introduce a methodology for designing benchmarks for NISQ devices, and implement them on several which are publicly available.

Benchmarking

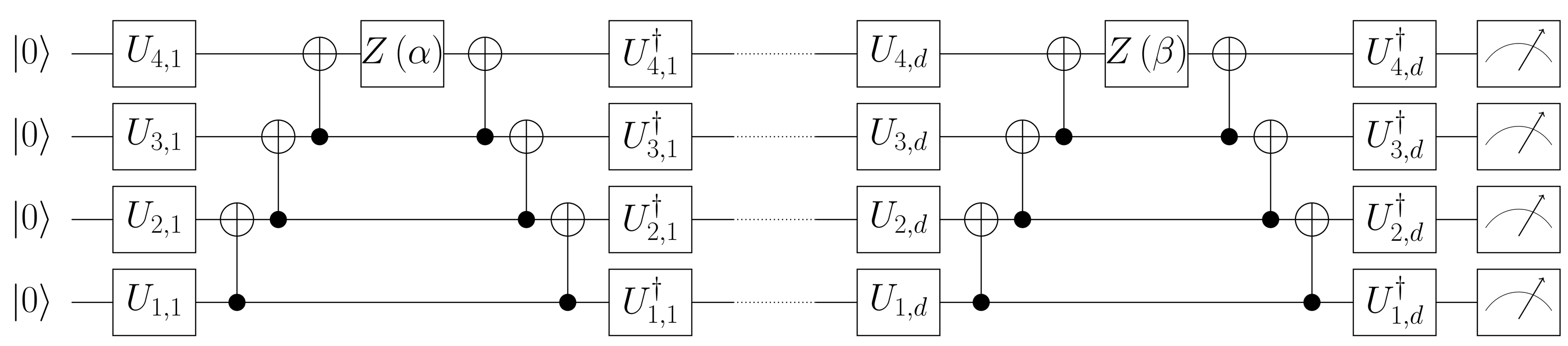
We suggest selecting separately, and guided by an application of concern, the circuits and figure of merit.

Circuits: Motivated by our interest in demonstrations of quantum supremacy, and in applications such as quantum chemistry.

Random circuits [1]: Random two qubit gates and permutations. Sampling from the output distribution is classically hard.



Pauli gadgets [2]: Random Pauli gadgets, with application in variational quantum eigensolvers.



Figures of merit: Measure the accuracy of the real distribution in approximating the ideal one. We use the following:

Cross entropy difference [3]: Related to the circuit fidelity so measures the impact of noise and guides its correction.

Heavy output probability [4]: Probability of reproducing likely (heavy) outputs of the ideal distribution. High reproduction probability is classically hard so indicates supremacy.

Compilation

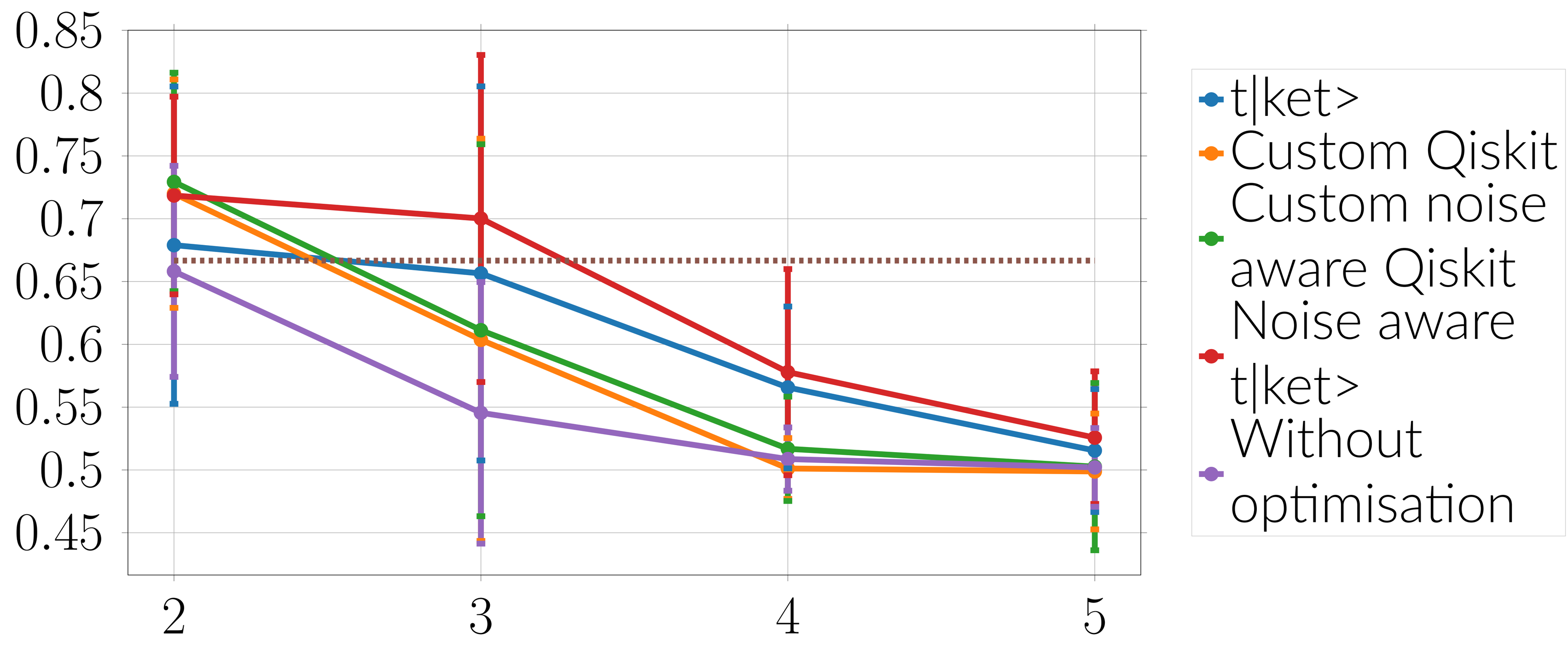
The accuracy of an implementation of a unitary depends on the circuit depth and gate count, and qubit noise levels. Hence, the compiler should be incorporated into the benchmark. We consider:

Noise aware placement: Adjusting the choice of qubits used by the circuit according to the qubit noise levels.

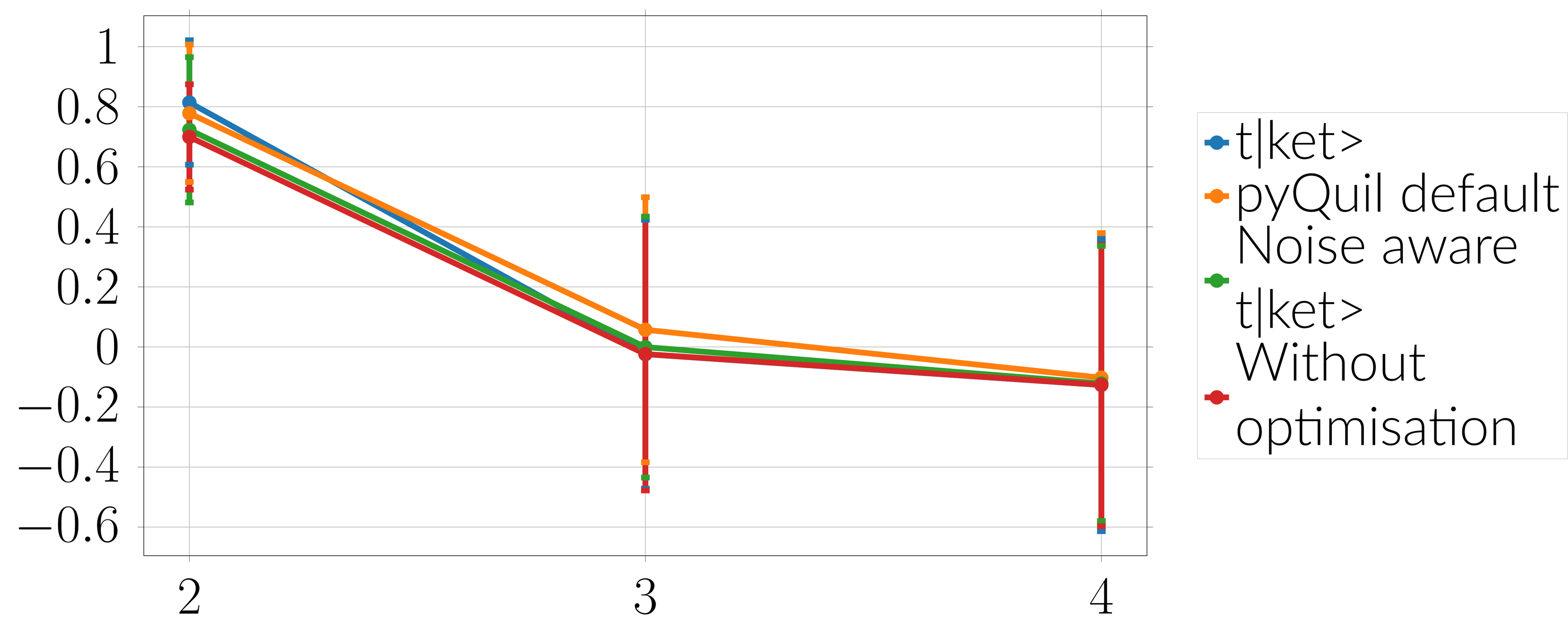
t|ket> vs default compilers: Optimised t|ket> compiler vs other default and custom compilers in common software packages.

Connectivity vs noise: Comparative benefits of qubit connectivity as opposed to gate fidelity and qubit degradation.

Results



Above is heavy output production probability data, as a function of the circuit width and averaged over 300 circuits, for the 14 qubit ibmq_16_melbourne device with random circuits. The error bars indicate one standard deviation. We see the comparative benefit of using the t|ket> compiler, and noise aware initial placement. Notice that by incorporating software into benchmarks we understand how best to extract power from a fixed device.



Above is cross-entropy difference data for the 5 qubit Aspen-4-5Q-C device with Pauli gadget circuits, again as a function of width and over 300 circuits. Notice the reduced impact of the noise awareness when the size of the device is smaller; a theme found throughout our benchmarking. We see limited improvement between the compilers, possibly resulting from high connectivity.

References

[1] Andrew W Cross, Lev S Bishop, Sarah Sheldon, Paul D Nation, and Jay M Gambetta. Validating quantum computers using randomized model circuits. *Physical Review A*, 100(3):032328, 2019.

[2] Alexander Cowtan, Silas Dilkes, Ross Duncan, Will Simmons, and Seyon Sivarajah. Phase gadget synthesis for shallow circuits. *arXiv preprint arXiv:1906.01734*, 2019.

[3] Sergio Boixo, Sergei V Isakov, Vadim N Smelyanskiy, Ryan Babbush, Nan Ding, Zhang Jiang, Michael J Bremner, John M Martinis, and Hartmut Neven. Characterizing quantum supremacy in near-term devices. *Nature Physics*, 14(6):595, 2018.

[4] Scott Aaronson and Lijie Chen. Complexity-theoretic foundations of quantum supremacy experiments. In *32nd Computational Complexity Conference (CCC 2017)*. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2017.

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