Qubit-efficient entanglement spectroscopy using qubit resets

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- Design new NISQ algorithms for entanglement spectroscopy.
  - Task: given copies of $|\psi\rangle_{AB}$ and a parameter n, estimate $\mathrm{Tr}(\rho_A^n)$.
  - Require **asymptotically fewer qubits** than any previous efficient algorithm; but still similarly noise-resilient.
  - Key tool: qubit reset
  - Test using numerical simulations and on Honeywell System HØ.

- Define *effective circuit depth* to explain results and analyze future algorithms using qubit resets.

Entanglement spectroscopy

- At a high level, goal is to understand the entanglement of a state $|\psi\rangle$.
  - e.g. $|\psi\rangle$ is output of some quantum simulation

- In particular, understand the bipartite entanglement of $|\psi\rangle_{AB}$ on systems A and B.
  - Fully characterized by the eigenvalues of reduced state $\rho_A = \mathrm{Tr}_B(|\psi\rangle\langle\psi|)$.
  - Learning the spectrum yields more information than entropy alone.
  - Important for understanding topological order, phase transitions, whether a system obeys an area law (and thus can be simulated classically), …

Entanglement spectroscopy

- Formally: Given as input a parameter n and black-box access to a circuit preparing $|\psi\rangle_{AB}$, estimate $\mathrm{Tr}(\rho_A^n)$.
  - Note not $\mathrm{Tr}(\rho_A^{\otimes n})$.

- The first few traces often can be used to reconstruct the largest few eigenvalues of ρ_A, which are often sufficient for applications.

  [Li, Haldane 08], [Johri, Steiger, Troyer 17], …

- Directly related to n-th Rényi entropy: $S_n(\rho) = \frac{1}{1-n}\log\big(\mathrm{Tr}(\rho^n)\big)$.

Previous algorithms for $\mathrm{Tr}(\rho_A^n)$

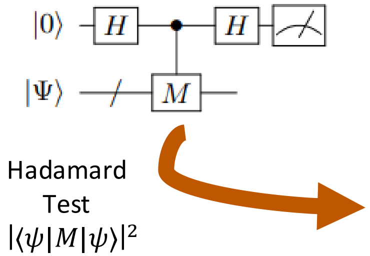
- Two known efficient, NISQ-friendly algorithms:
  - HT – a variant of the Hadamard Test

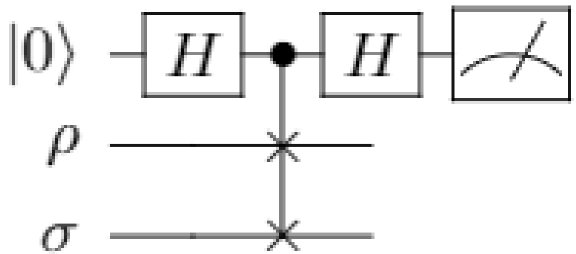
    [Johri, Steiger, Troyer 17]
  - **TCT** – a variant of the Two-Copy Test

    [Subaşı, Cincio, Coles 19]

Previous algorithm #1 for $\mathrm{Tr}(\rho_A^n)$
The HT

- Recall SWAP Test:



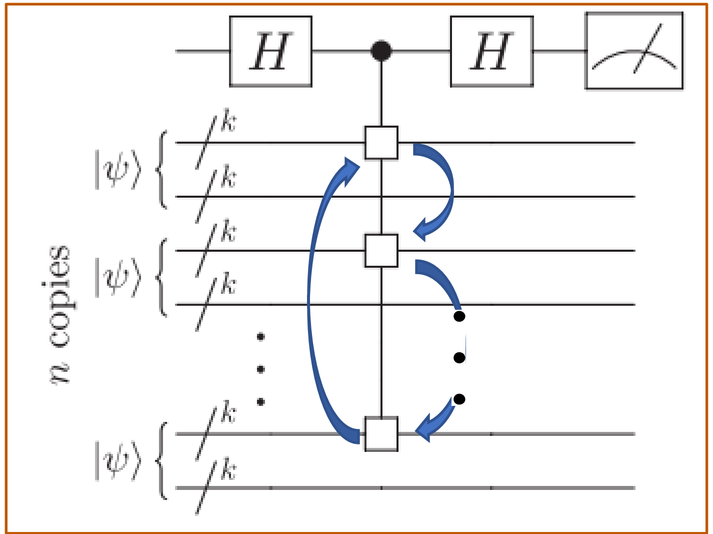


When $\rho = \sigma$, gives

$$\mathrm{Tr}(\mathrm{SWAP}\rho \otimes \rho) = \mathrm{Tr}(\rho^2)$$

- Generalize [Johri, Steiger, Troyer 2017]:
  Use Cyclic Permutation operator P_A^{cyc} on n copies of $|\psi\rangle$ to compute $\mathrm{Tr}(\rho_A^n)$.

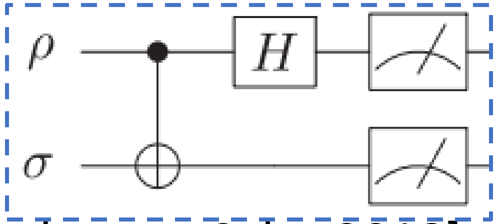
HT =



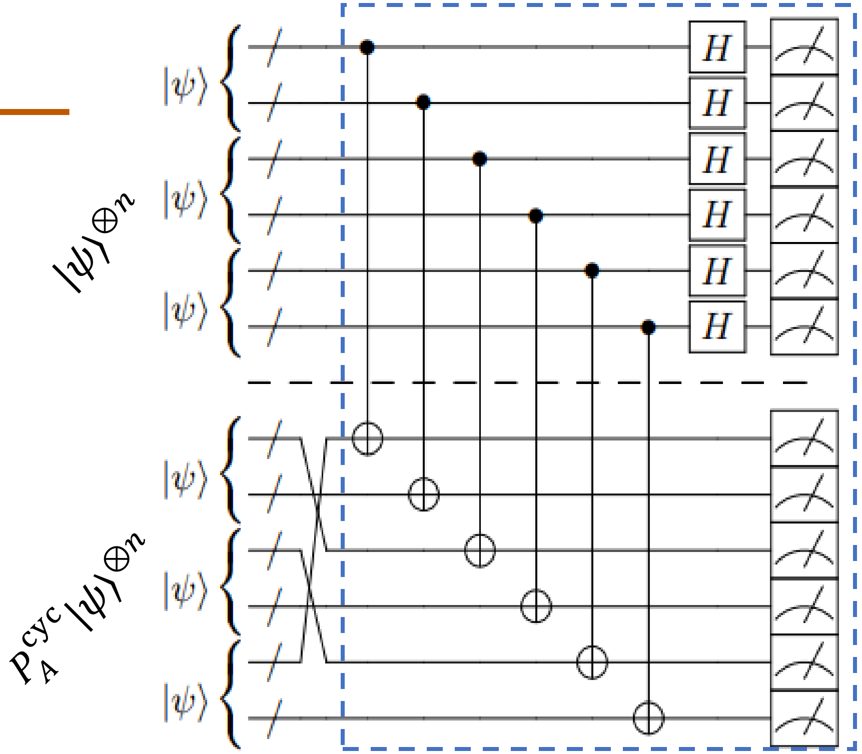
Cyclic Permutation:
e.g. 1234 → 4123

Previous algorithm #2 for $\mathrm{Tr}(\rho_A^n)$
The TCT

- Bell Basis ($|\phi^+\rangle, |\phi^-\rangle, |\psi^+\rangle, |\psi^-\rangle$) is an eigenbasis of SWAP.
- A Bell Basis Measurement: a CNOT, an H, and classical postprocessing.



→[Garcia-Escartin, Chamorro-Posada 2013] [Cincio, Subaşı, Sornborger, Coles 2018]
Can simulate SWAP Test and measure state overlap using a Bell Basis Measurement.



- [Subaşı, Cincio, Coles 2019]
Measure overlap of $|\psi\rangle^{\otimes n}$ and $P_A^{\mathrm{cyc}}|\psi\rangle^{\otimes n}$

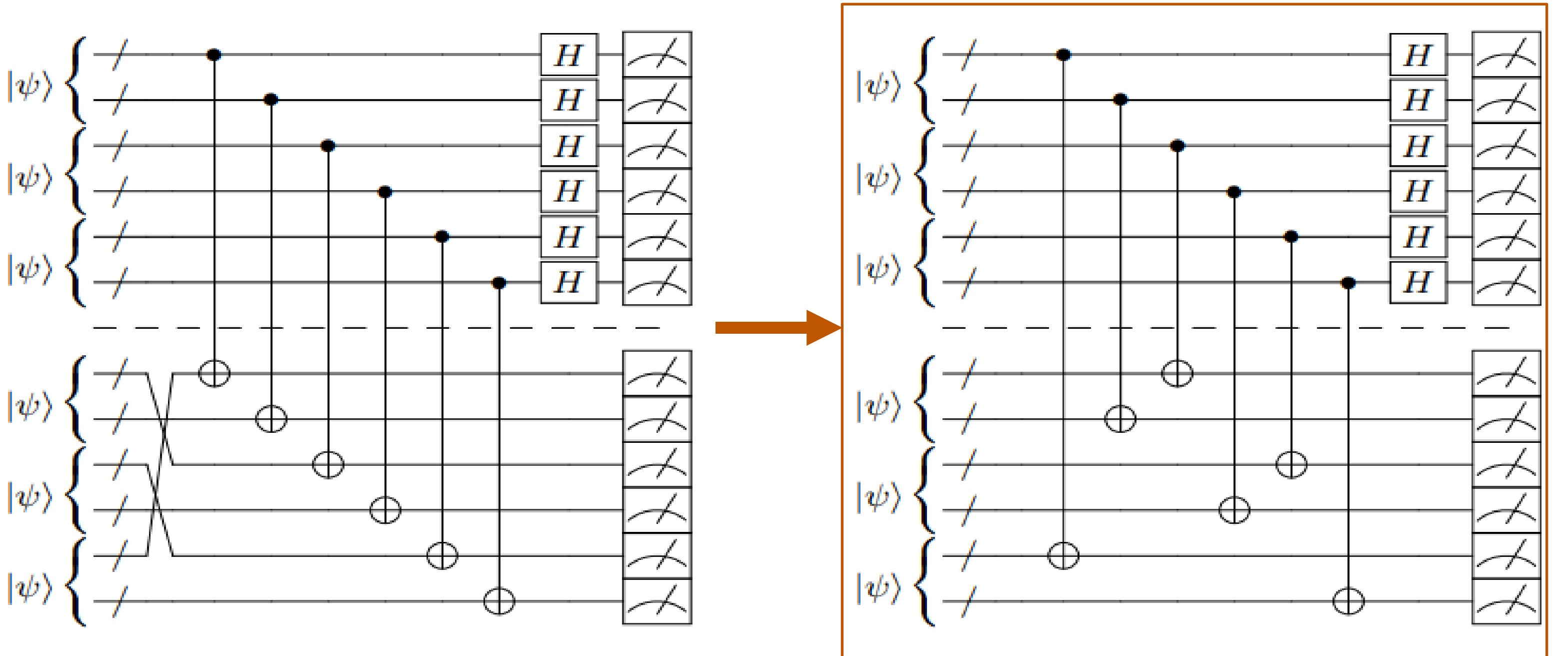
$$\left|\langle\psi|^{\otimes n} P_A^{\mathrm{cyc}} |\psi\rangle^{\otimes n}\right|^2 = \mathrm{Tr}(\rho_A^n)^2$$

$$\rightarrow \mathrm{Tr}(\rho_A^n)$$

Previous algorithm #2 for $\mathrm{Tr}(\rho_A^n)$ The TCT

[Subaşı, Cincio, Coles 2019] Using Bell-basis Measurement to measure overlap of $|\psi\rangle^{\otimes n}$ and $P_A^{\mathrm{cyc}}|\psi\rangle^{\otimes n}$ to estimate $\mathrm{Tr}(\rho_A^n)$

- Neat trick: Apply P_A^{cyc} without any gates.
  Just reindex the CNOTs and the postprocessing formula.
- $O(1)$ depth: 1 layer of CNOT, 1 layer of H



Our qubit-efficient algorithms

- Where $|\psi\rangle$ is $2k$ qubits,
  - HT requires $2nk = O(nk)$ qubits
  - TCT requires $4nk = O(nk)$ qubits

- We give variants of HT and TCT to compute $\mathrm{Tr}(\rho_A^n)$ that require $O(k)$ qubits (as few as $3k + 1$).
  Independent of n. An asymptotic difference.

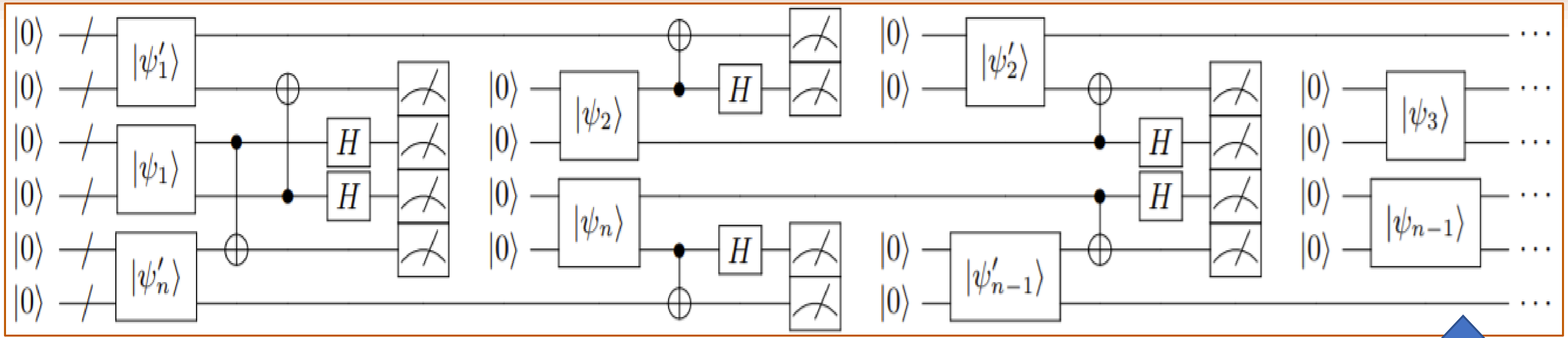
- Our new, low-width circuits have larger depth.
  But, we use qubit resets to avoid the usual noisy affects.

Qubit resets

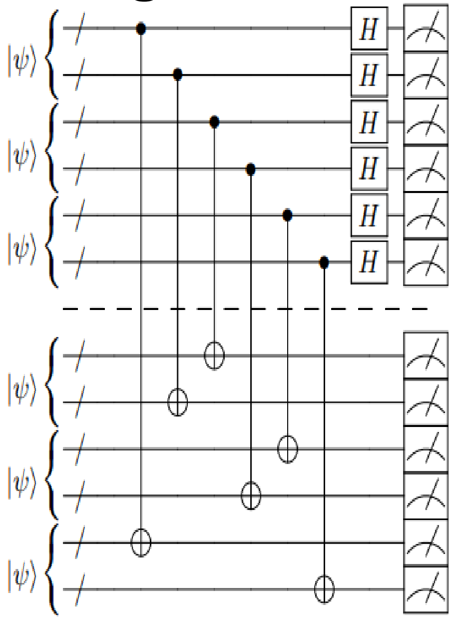
- We usually think of "resetting" qubits to their $|0\rangle$ state at the beginning & end of a computation.
- "Intermediate measurement and reset" is now being rolled out by Honeywell, IonQ, IBM, etc.
- Can reset, i.e. drive back to $|0\rangle$ state, individual qubits in time comparable to a measurement.
  Then, reuse it.
- They're an underexplored tool that will be crucial for NISQ:
  - [Rattew, Sun, Minssen, Pistoia 20] [Foss-Feig et al 20] [Liu, Zhang, Wan, Wang 19] and just a few other examples to date.

Our algorithm: qe-TCT

qe-TCT



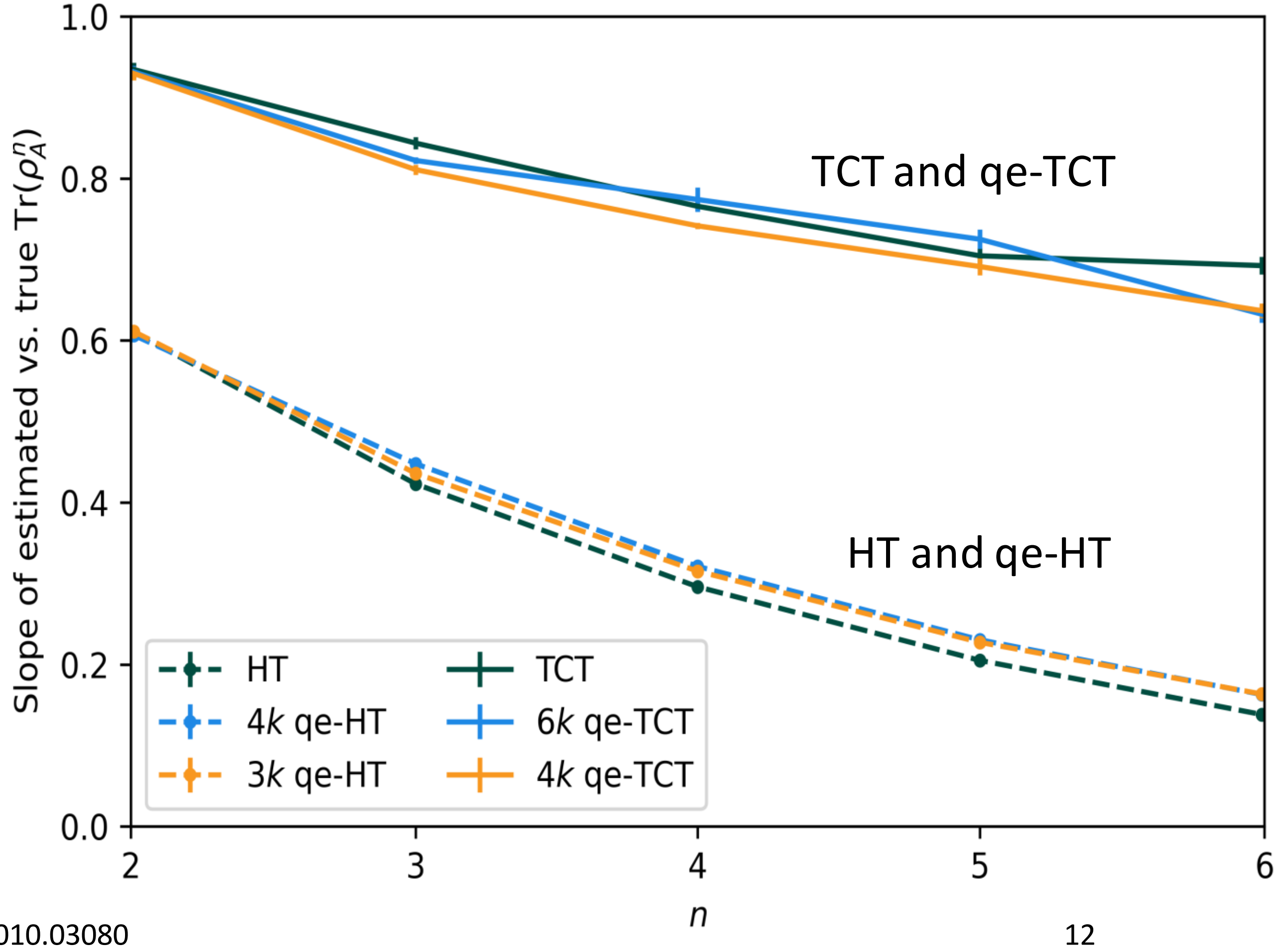
Original TCT



- A new $|0\rangle$ is a qubit reset.
- Each $|\psi_i\rangle$ is identical; indexing just for convenience
- Quick check: each copy only interacts with two other copies.
- **Key intuition**: When a register finishes its interactions, measure, reset, and reuse to load a new copy. Repeat as necessary for n.
- So, number of qubits to compute $\mathrm{Tr}(\rho_A^n)$ is independent of n

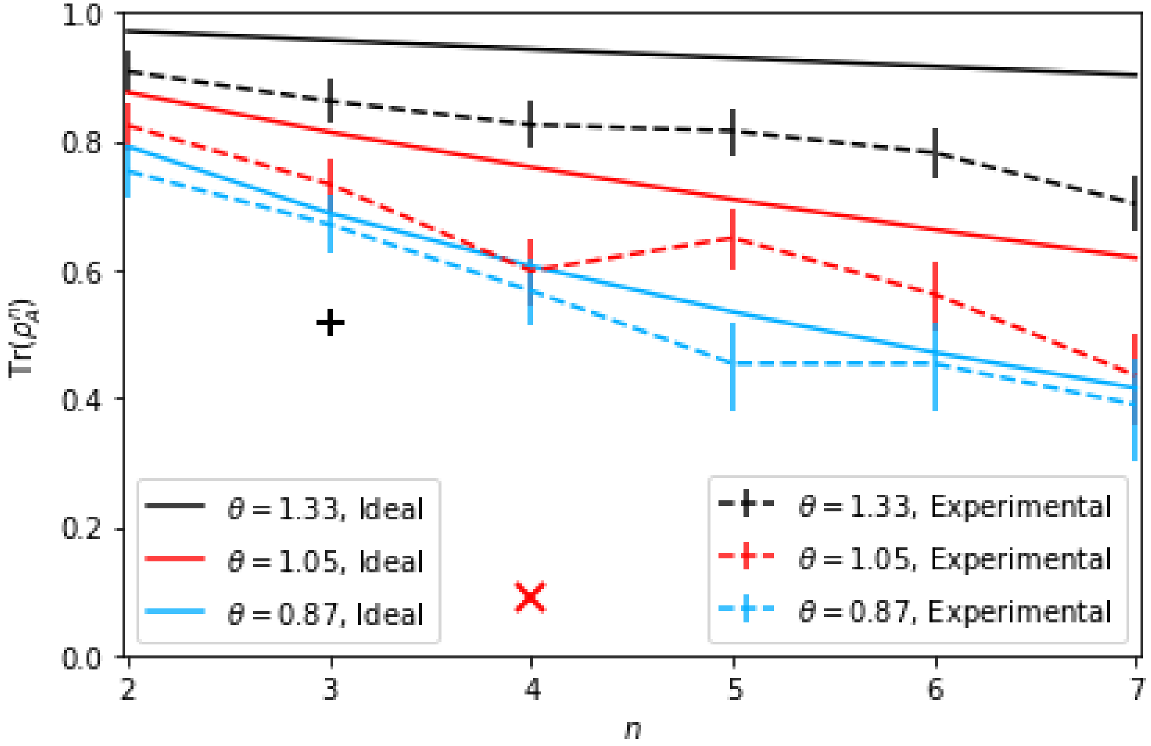
Numerical simulations

- Tested our algorithms and previous algorithms under simulated gate, thermal, and readout noise (see paper for noise parameters).
- Input different $|\psi\rangle$ with varying entanglement.
  For each value of n, use slope of true $\mathrm{Tr}(\rho_A^n)$ vs estimated $\mathrm{Tr}(\rho_A^n)$ to determine quality of algorithm.
  We plot the slopes.
- **Takeaway**: The new algorithms perform similarly to original.
  HT and qe-HT TCT and qe-TCT



Honeywell system HØ

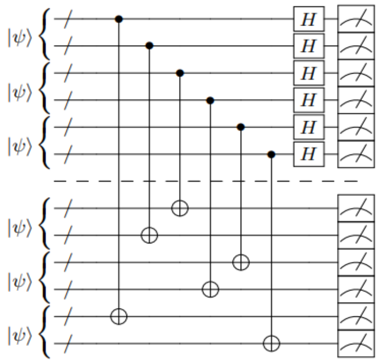
- Tested on Honeywell 6-qubit ion trap quantum computer.
- We ran qe-TCT on three 2-qubit states up to $n = 7$.
  The original TCT would require 28 qubits, more than the 6 available.



Effective depth

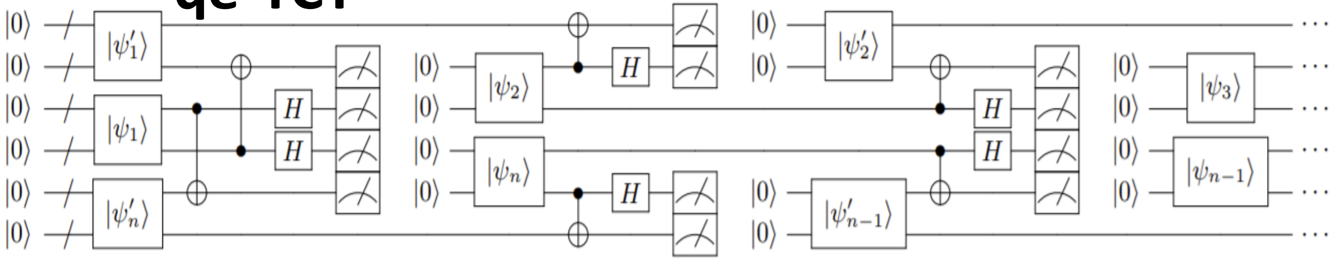
- Circuit depth is interesting because:
  1. Able to prove things about bounded-depth circuits like AC_0, QNC_0, etc.
  2. It's a good heuristic for susceptibility to thermal relaxation and decoherence noise: i.e., deeper circuits perform worse.
- Depth is a bad heuristic for circuits using resets.
  - Evidence: Our circuits!

  - Original TCT has $O(1)$-depth
  - qe-TCT has $\widetilde{\Theta}(n)$-depth
  - Asymptotic difference, but they perform similarly.



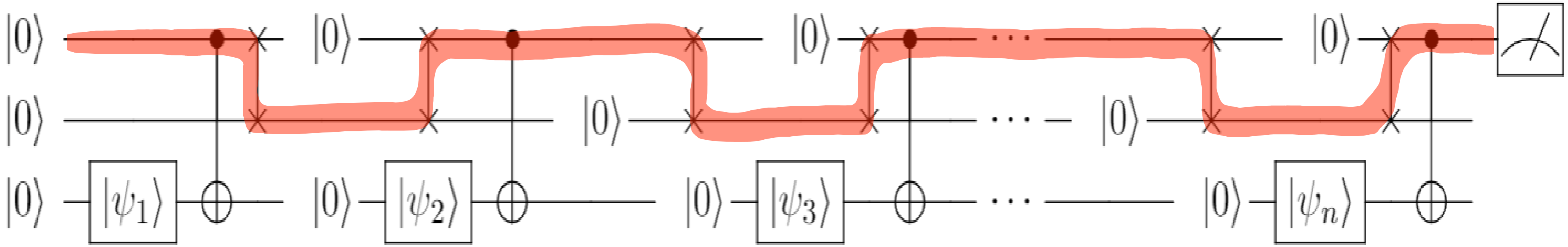
Original TCT

qe-TCT



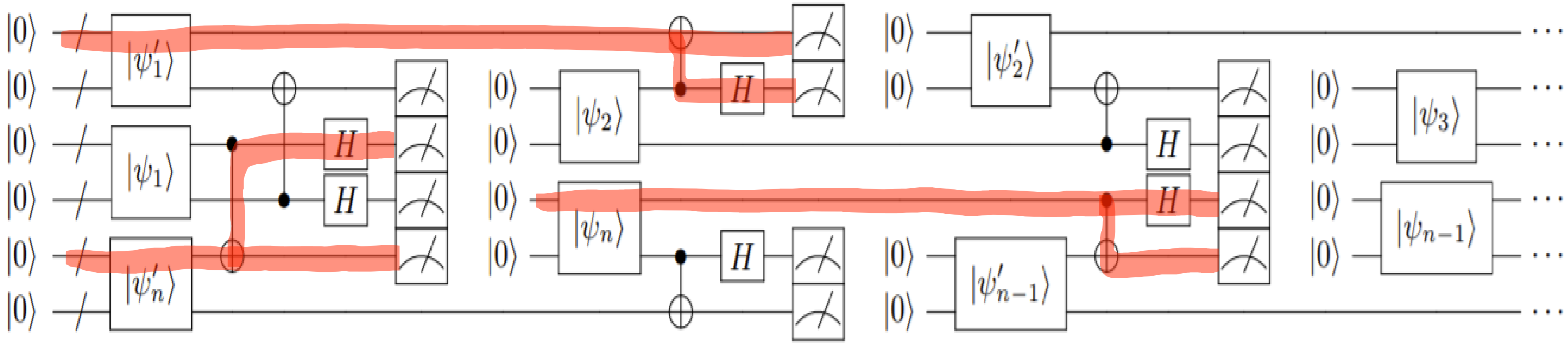
Effective depth

- Naïve idea: longest time any qubit goes between resets
- Counterexample:



Effective depth

- Effective circuit depth: maximum length of a path along which there is information flow.
- Then, both the Original TCT and qe-TCT have *effective depth* equal to $O(1)$. ✓



- Reduces to standard depth for circuits without resets.

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- New algorithms for estimating $\mathrm{Tr}(\rho_A^n)$ which require asymptotically fewer qubits but achieve similar noise resilience.
  Enable spectroscopy of larger quantum systems on NISQ devices than previously possible.
- *Effective circuit depth* generalizes standard depth to circuits using qubit resets. Useful for predicting noise-resilience of future circuits.
- Open: What other algorithms and applications can be made NISQ-ready using qubit resets?