Large-Scale Entanglement on Physical Quantum Computers

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Noisy intermediate Scale Quantum (NISQ) Computing

Benchmark devices: measure extent of quantumness
Overview

Benchmarking quantum devices

Forms of Multipartite Entanglement
- Bipartite and Genuine Multipartite entanglement

Detecting **Bipartite entanglement**
- By preparing Graph states on *IBM Quantum* devices

Detecting **Genuine multipartite entanglement**
- By preparing GHZ states
- GHZ decoherence rates

Bell state teleportation
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Pure State Entanglement - Definitions

- Entanglement
  - Non-classical correlations
  - State is not separable: $|\psi\rangle \neq |\phi_1\rangle \otimes |\phi_2\rangle$, for any $|\phi_1\rangle$ and $|\phi_2\rangle$
  - State is entangled

- Multiqubit Entanglement
  - A multiqubit state either:
    - "is fully bipartite entangled"
    - (aka "is entangled")
    - "contains bipartite entanglement"

$|\text{Bell}\rangle = \sqrt{2}|00\rangle + |11\rangle$

$|\text{GHZ}\rangle = \sqrt{2}|000\rangle + |111\rangle$

$|\psi\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$

Entanglement graph
Qubit energy levels
Fully Bipartite Entangled (aka entangled)
Contains Bipartite Entanglement

Bipartition $\{0\}$ and $\{1,2\}$: Entangled
Bipartition $\{0,1\}$ and $\{2\}$: Separable
What is Mixed State Entanglement?

Real quantum device → Noise
- Quantum state is a **Mixed state**: probabilistic mixture of pure states
- More complicated than pure states

**Mixed State**
\[
\rho = \sum_{i=1}^{N} p_i \rho_i
\]
- Density matrix ρ
- Probabilities p_i

Quantum Theory: Concepts and Methods, (1993)

**Bipartite Entangled (or just Entangled)**
- State is not separable, i.e. \( \rho \neq \rho^A \otimes \rho^B \), for all bipartitions A and B
- Although, individual pure states \( \rho_i \) might be separable

**Genuine Multipartite Entangled (GME)**
- Stronger form of entanglement
- There is always a fully entangled pure state

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Bell state teleportation
Choose a quantum state to prepare

Graph State (Cluster State)

- Robust to noise
  - Requires $n/2$ local measurements to disentangle
- Low circuit depth
- Convenient for detecting bipartite entanglement

- Applications
  - One-way quantum computing
  - Fault-tolerant error correction
  - Measurement-Based variational quantum eigensolver

How do we detect entanglement?

Graph representation

\[
|G_n\rangle = \prod_{(\alpha, \beta) \in E} CZ_{\alpha\beta} |+\rangle^\otimes n
\]

$E := \text{edge set}$

Controlled-phase gate

Defined on a graph

Graph States


Controlled-phase gate

Preparation

Circuit representation

Quantum State Tomography (QST)

- Get a density matrix, encapsulating noise
  - $2^N \times 2^N$ complex matrix
- Analyse entanglement properties

Full quantum state information
- Can be overkill for measuring a particular property
- Use a detection strategy

Requires $3^N$ circuits
- 6 qubits: 729 circuits
- 10 qubits: ~59,000 circuits
- 20 qubits: ~3.5 Billion circuits!

1 day $\approx$ 15-30k circuits (approx)
Focus on bipartite entanglement

Detection Strategy
- State is not separable
  ⇒ State is at least bipartite entangled

1. Generate entanglement graph
   - Measure entanglement between qubit pairs
2. Is entanglement graph connected?

Example: Separable State
Entangled pairs:
(0, 1)
(1, 3)
(2, 4)
⇒ not entangled

So if connected, then entangled

On Quantum Devices
To show: entanglement graph is connected
Perform state tomography on qubit pair and their neighbours

**Graph State Property:**
Project neighbouring qubits to Z-basis states → Bell state (up to local operations)

- Bell states produced from combinations of states \( \{0, 1\}^{\#(\text{neighbours})} \):
  
  \[
  \begin{align*}
  H \otimes I |\Phi^+\rangle &= (|00\rangle + |01\rangle + |10\rangle - |11\rangle) / 2 \\
  H \otimes X |\Phi^+\rangle &= (|00\rangle + |01\rangle - |10\rangle + |11\rangle) / 2 \\
  XH \otimes I |\Phi^+\rangle &= (|00\rangle - |01\rangle + |10\rangle + |11\rangle) / 2 \\
  XH \otimes X |\Phi^+\rangle &= (|00\rangle - |01\rangle - |10\rangle - |11\rangle) / 2 
  \end{align*}
  \]

Calculate entanglement for each set of states \( \{0, 1\}^{\#(\text{neighbours})} \)

**Negativity** of partial transpose

- Calculate \( \rightarrow \) Sum over magnitudes of negative eigenvalues of \( \rho_{3,4}^{T_A} \)
- For **Two Qubits**: Non-zero negativity is necessary and sufficient
  
  - Negativity is non-zero \( \iff \) Entanglement  
  

Measure negativity for all neighbour states: \( \{0, 1\}^{\#(\text{neighbours})} \)

\( \rightarrow \) Extent of entanglement is the largest negativity (among the combinations)

Wang et. al. npj Quantum Information (2018)
Results: Negativities on an *IBM Quantum* device

Apply these techniques on an IBM Quantum computer: the **20-qubit ibmq_poughkeepsie** device
- Embed a line graph state
- Generate entanglement graph

- Whole device is bipartite entangled
- At the time → largest quantum entangled state (on a universal quantum computer)
- Previous record was 16 qubits  

**Hardware Layout**

*20-qubit ibmq_poughkeepsie* device

- Error rates:
  - Readout: 3.8%, $\sigma = 1.6%$
  - CNOT: 2.3%, $\sigma = 0.8%$

- Decoherence times:
  - $T_1 = \sim 100 \mu s$ (relaxation)
  - $T_2 = \sim 100 \mu s$ (dephasing)

**Entanglement in ibmq_poughkeepsie device**


**Entanglement Graph**

(all qubits connected)

State is bipartite entangled

**Scale up to larger devices**
Native Graph State

Native graph state: match the hardware layout

- Benchmark qubit pairs
- More connected cycles
  - Requires more separable pairs to break connectedness
- Still constant circuit depth
  - Depth = largest neighbour count of qubits

Hardware Layout

53-qubits

Constant depth → largest neighbour count of qubits
Quantum Readout-Error Mitigation (QREM)

- Readout assignment errors:
  - Obfuscates quantum data
  - State appears less entangled than it is

Calibrate readout-errors with stochastic matrix $A$:

$$A\tilde{p} = \tilde{p}_{\text{noisy}}$$

$$\rightarrow \tilde{p} = A^{-1}\tilde{p}_{\text{noisy}}$$

$$A = \bigotimes_{i=1}^{N} A_i$$

$$A_i = \begin{pmatrix} p_i(0|0) & p_i(0|1) \\ p_i(1|0) & p_i(1|1) \end{pmatrix}$$

Calibration matrix for qubit $i$

Requires only 2 measurements $\{|00 \ldots 0\rangle, |11 \ldots 1\rangle\}$

$$A^{-1} = \bigotimes_{i=1}^{N} A_i^{-1}$$

- Efficient application
  - Apply each qubit calibration matrix separately, zeroing small probabilities
  - M3 python package
  - Make physical


Nation et al. PRX Quantum (2021)

Results: Newer IBM Quantum devices

53-qubit `ibmq_rochester` device

Error Rates:
- Readout: 12.6%, $\sigma = 9.3\%$
- CNOT: 4.6%, $\sigma = 2.4\%$

Decoherence Times:
- $T_1 \approx 53 \mu$s (relaxation)
- $T_2 \approx 53 \mu$s (dephasing)

65-qubit `ibmq_manhattan` device

Error Rates:
- Readout: 2.1%, $\sigma = 1.5\%$
- CNOT: 1.5%, $\sigma = 0.6\%$

Decoherence Times:
- $T_1 \approx 60 \mu$s (relaxation)
- $T_2 \approx 78 \mu$s (dephasing)

Results: Entanglement Graphs

53-qubit ibmq_rochester device

Bipartite entangled regions

65-qubit ibmq_manhattan device

Bipartite entangled region → whole device

53 qubits

→ Whole-device bipartite entanglement

65 qubits

→ Whole-device bipartite entanglement

Scale up to larger devices

Let’s Look at the Required Resources

Quantum State Tomography on Each Pair
Requires $3^N$

- $N = 4$ qubits $\rightarrow 3^4 = 81$ circuits ($\sim 350k$ shots*)
- $N = 5$ qubits $\rightarrow 3^5 = 243$ circuits ($\sim 1$ Million shots*)

* at $\sim 4000$ shots each

53-qubit Rochester:
- 58 qubit pairs
  - $\sim 11,000$ circuits
  - Or $\sim 44$ Million shots

65-qubit Manhattan:
- 72 qubit pairs
  - $\sim 14,000$ circuits!
  - Or $\sim 56$ Million shots!

Could take a **whole day** to complete
- Was barely executing within device calibration cycles

We need to go higher
Target: 127-qubit *ibm_washington* device

127-qubit Washington:
- 142 pairs of qubits
  - ~28,000 circuits
  - Or ~112 Million shots!
  - Error bars: x8 more

How to reduce this?

Two Optimisation Techniques
1. Neighbour-state bucketing
2. Parallel Quantum State Tomography

Error Rates:
- Readout: 2.3%, $\sigma = 2.8\%$
- CNOT: 0.8%

Decoherence Times:
- $T_1 = \sim 240 \, \mu s$ (relaxation)
- $T_2 = \sim 142 \, \mu s$ (dephasing)
Optimisation 1: Neighbour-State Bucketing

Currently

• Tomography on qubit pair and neighbours (4 or 5 qubits)

➢ 5 qubits → requires $3^5 = 243$ circuits per pair

However

• Projecting neighbours only ever results in 1 of 4 Bell state variations

1. $|\Phi^{BS1}\rangle \equiv H \otimes I |\Phi^+\rangle = (|00\rangle + |01\rangle + |10\rangle - |11\rangle) / 2$
2. $|\Phi^{BS2}\rangle \equiv H \otimes X |\Phi^+\rangle = (|00\rangle + |01\rangle - |10\rangle + |11\rangle) / 2$
3. $|\Phi^{BS3}\rangle \equiv XH \otimes I |\Phi^+\rangle = (|00\rangle - |01\rangle + |10\rangle + |11\rangle) / 2$
4. $|\Phi^{BS4}\rangle \equiv XH \otimes X |\Phi^+\rangle = (|00\rangle - |01\rangle - |10\rangle - |11\rangle) / 2$

▪ Bucket based on obtained Bell state
▪ Perform 2-qubit tomography

• Requires only $3^2 = 9$ circuits per pair

• 127-qubit Washington:
  • From ~28,000 circuits
    ➢ down to 1,278 circuits!
    ➢ A factor of 22 saving

John F. Kam, et. al., paper in preparation
Optimisation 2: Parallel Quantum State Tomography

Currently
• Tomography on each qubit pair separately

Instead
• Perform in parallel on non-overlapping sets of qubit-pairs and their neighbours
• Only need up to **8 rounds** for IBM Quantum heavy-hexagonal layouts
  • Using layout-agnostic greedy algorithm
  • Can reduce to **4 rounds** when sharing neighbours

• **127-qubit Washington:**
  • Originally ~28,000 circuits
  • Then 1,278 circuits (neighbour-state bucketing)
    ➢ down to **constant 36 circuits**! (Parallel-QST)

• 36 circuits for all heavy hex layouts

John F. Kam, et. al., paper in preparation
Results: 127-qubit ibm_washington Device

127-qubit ibm_washington device

No QREM

QREM

127 qubits

→ Whole-device bipartite entanglement

John Fidel Kam et al., (paper in production)
Latest: **433-qubit ibm_seattle Device**

**Device (ibm_seattle):**
- 19 inactive qubits
- 433 $\rightarrow$ 414 active qubits

Error rates (mean):
- Readout: 7.6%, $\sigma$ = 7.4%
- CNOT: 2.9%, $\sigma$ = 3.4%

Decoherence times:
- $T_1$ = $\sim$90 $\mu$s (relaxation)
- $T_2$ = $\sim$60 $\mu$s (dephasing)

**Experiment:**
Originally $\sim$100,000 circuits
➢ down to **36 circuits**!

**Result:**
- Graph state is bipartite entangled
- All active qubits

John Fidel Kam *et al.*, (paper in production)
Relation to physical device

Benchmark: how does it relate to device?

Errors of all CNOTs directly involved

Negativity of qubit pair

Individual couplings for 127-qubit *ibm_washington*

Negativity of qubit pair

Mean CNOT Error $R = -0.388$

(directly involved CNOTs)
All Device Errors vs. Entanglement

Device Negativities (readout-error mitigated)

<table>
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<tr>
<th>Device</th>
<th>Qubits</th>
<th>QV</th>
<th>Mean $N$</th>
<th>Whole-Device</th>
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<td>16</td>
<td>$0.482 \pm 0.007$</td>
<td>✓</td>
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<tr>
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<td>Seattle</td>
<td>433</td>
<td></td>
<td>0.340</td>
<td>✓ (active)</td>
</tr>
</tbody>
</table>

Averaged device negativities vs CNOT errors

\[ R = -0.643 \]

Seattle 433 - 0.340 (active)

Quantum Volume

4-qubit ibmq_manila

7-qubit ibm_oslo

16-qubit ibmq_guadalpe

27-qubit ibm_cairo
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Detecting Genuine multipartite entanglement

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• GHZ decoherence rates

Bell state teleportation
**GHZ States**

- GHZ State → generalisation of Bell state to more qubits
  
  \[ |\text{Bell}\rangle = \frac{|0\rangle^\otimes 2 + |1\rangle^\otimes 2}{\sqrt{2}} \rightarrow |\text{GHZ}_N\rangle = \frac{|0\rangle^\otimes N + |1\rangle^\otimes N}{\sqrt{2}} \]

- Conveniently sparse density matrix

- Sensitive to noise
  - Disentangled after only 1 local measurement
  
  \[ \frac{|000\rangle + |111\rangle}{\sqrt{2}} \rightarrow \{|000\rangle, |111\rangle\} \]

**GHZ State** density matrix (4-qubit):

\[
\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{pmatrix} / 2
\]

**Graph State** density matrix (4-qubit):

\[
\begin{pmatrix}
1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\
1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\
1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\
-1 & -1 & -1 & 1 & -1 & 1 & -1 & 1 \\
1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\
1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 \\
-1 & -1 & -1 & 1 & -1 & 1 & -1 & 1 \\
1 & 1 & 1 & -1 & 1 & 1 & -1 & 1
\end{pmatrix} / 8
\]

**Preparation**

- **Hadamard**
  
  \[ \frac{|00...0\rangle + |11...1\rangle}{\sqrt{2}} \]

- **Grow the state with CNOTs**

**All-to-all connectivity:**

(CNOT Depth) \( \approx \log_2 N \)

Cruz et al., Adv. Quantum Technol (2019)

**IBM Quantum Heavy Hex Layout:**

(CNOT Depth) \( \approx \sqrt{2N} \)

Genuine Multipartite Entanglement (GME) in GHZ states

GHZ Fidelity (> 0.5) → GME

Fidelity = (Population)/2 + (Coherence)/2
- Population: Occupancies of \(|00 \ldots 0\rangle\) and \(|11 \ldots 1\rangle\)
- Coherence: Multiple Quantum Coherences (MQC) \[ \text{Coherence} = 2 \frac{I_N}{N} \]

Multiple Quantum Coherences (MQC)

Ideal GHZ State

\[ |00 \ldots 0\rangle + |11 \ldots 1\rangle \]

\[ \frac{1}{\sqrt{2}} \]

Overlap Signal:
Occupancy of \(|00 \ldots 0\rangle\)

Coherence = \(2 \sqrt{I_N}\)

I_N: Amplitude of overlap signals

Hahn Echo: Refocussing \(\pi\)-pulse
(Reduce qubit phase errors)

Ideal state: phase of \(N\phi\)

\[ |00 \ldots 0\rangle + e^{iN\phi} |11 \ldots 1\rangle \]

\[ \frac{1}{\sqrt{2}} \]

Results: On the 27-qubit `ibmq_montreal` device

- Prepare on device
- Add parity verification → effects on fidelity → discard when measure 1

- 27-qubit GME, whole device!
- Next: Scale to larger devices

Fidelity with 2 parity checker qubits (q2 and q24)

QREM : Quantum Readout-Error Mitigation

Parity checking qubits

GHZ state circuit

The GHZ Embedding Algorithm

1. Select a qubit
   a) Breadth first search
   b) Preference CNOTs with low error

2. Repeat 1. for each qubit and choose the best embedding

John F. Kam, et. al., paper in preparation
Results: *ibm_washington*

The 32-qubit GHZ is genuine multipartite entangled!

127-qubit *ibm_washington device*

**Fidelity**

![Fidelity Graph]

**Population**

![Population Graph]

**Coherence**

![Coherence Graph]

Genuine Multipartite Entangled!

John F. Kam, et. al., paper in preparation
History of Genuine Multipartite Entanglement

Experimentally prepared states shown to exhibit GME

- Superconducting systems
- Ion Trap
- Photon (Polarisation)
- Photon (Multiple DoF)
- NV Diamond
- Neutral Atom
- Quantum Dot

Mario Krenn, mariokrenn.wordpress.com
Preserving the GHZ State Fidelity

Wait after preparation

- **Spin Echo**
  - One $\pi$ pulses

- **Dynamical Decoupling**
  - A series of pulses

- **Periodic Dynamical Decoupling**
  - A series of $\pi$ pulses

Free Delay Circuits

Dynamical Decoupling

Spin echo

Periodic dynamical decoupling
Results: GHZ State Decay Curves

- Decay curves for 7-qubit state
- Measured Population
  - No real improvement
  - PDD gates introduce errors
- Measured Coherence
  - Big improvement
  - Idle phase are being cancelled
- Measured Fidelity
  - Big Improvement

Point of reference: (CNOT gate time) ≈ 400 ns

7-qubit GHZ state on the *ibmq_mumbai* device
Superdecoherence?

- Plot GHZ decoherence vs qubit count
- **Superdecoherence**
  - Qubit decoherence rates scale with system size
    - When qubits are coupled to the same reservoir
- **Previous work**
  - An Ion trap system → $N^2$ GHZ decoherence rate scaling
    - **Superdecoherence**
    - Up to 6-qubit GHZ states
  - IBM Quantum device → $N$ GHZ decoherence rate scaling
    - **No Superdecoherence**
    - Up to 8-qubit GHZ states
- Test on current IBM Quantum device
  - (CNOT gate time) ≈ 400 ns

\[ C^{(N)}(t) = C_0^{(N)} e^{-\alpha^{(N)} t} \]

\( \alpha \): GHZ decoherence rate


John F. Kam, et. al., paper in preparation
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Bell state teleportation
One-Way Quantum Computation

- Start with 2 entangled qubit states $|\alpha\rangle_0$ and $|\beta\rangle_1$
- Challenge: Teleport (or move) $|\beta\rangle_1$ across a chain of qubits
  - Keeping $|\alpha\rangle_0$ and $|\beta\rangle_1$ entangled
- Compare 3 approaches
  - Swap gates
  - Teleportation: Dynamic circuits
  - Teleportation: Post-selection

Using SWAP gates

- Start with 2-qubit Bell state
- Use SWAP gates to transport the state along a chain
- Circuit depth scales with chain length

\[ \text{SWAP}_{12} |q_1 q_2\rangle = |q_2 q_1\rangle \]
Teleportation: Dynamic Circuit

- Corrections are applied after each measurement
- Depth grows with qubit-measurement count

Diagram:

- Teleportation & Dynamic Circuit
- QST

Circuit components include:
- $|\phi(G_2)\rangle$
- $H$ gates
- Dynamic Measurements
- $U$ gates
- $c_0 : \sqrt{\frac{1}{2}}$
Teleportation: Post-Selection Circuit

- Bucket the teleported qubits into four possible Bell state variations
- Only 4 combinations → repeat until success
Comparisons

27-qubit ibmq_Mumbai device

Post Select

Dynamic Circuits
Dynamic Circuits & mitigated
SWAP
SWAP & mitigated
Post-Processed
Post-Processed & mitigated
Summary

Forms of Multipartite Entanglement
- Bipartite entanglement
- Genuine multipartite entanglement

Bipartite entanglement in graph states
- Constant 36-circuit algorithm
- Whole-device entanglement on up to 414-qubits
- Negativity correlated with CNOT fidelities
  John F Kam et. al. paper in preparation

Genuine multipartite entanglement in GHZ state
- GME across 32 qubits on *ibm_washington* device
- Looked at GHZ decoherence times
  - No superdecoherence
    John F Kam et. al. paper in preparation

Bell state teleportation
- Post-selected teleportation easily hopped over 11 qubits
  Haiyue Kang, et. al. paper in preparation