# Qubit Movement-Optimized Program Generation on Zoned Neutral Atom Processors

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# Introduction

- ▶ Zoned architectures improve gate fidelity ($> 99.9\%$ for 1Q, $> 99.5\%$ for 2Q).
- ▶ Standard quantum program structures are inefficient on zoned architectures, requiring excessive zone-to-zone transfers.
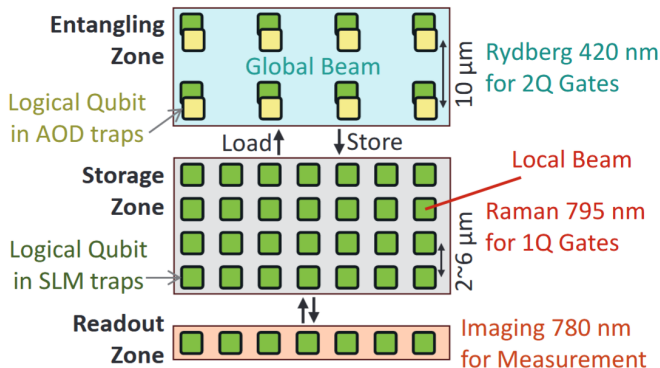


Figure: The entangling zone is dedicated to executing 2-qubit gates, while the storage zone is for single qubit gate.

# Motivation

- Naïve program execution causes 78-89% of runtime to be spent on zone-to-zone qubit transfers.
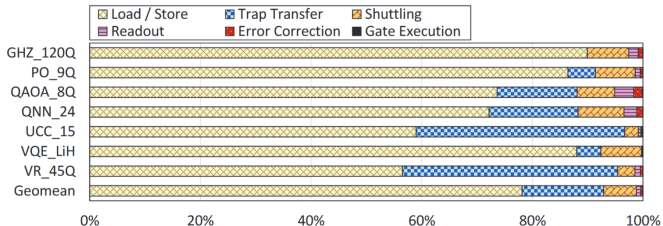- **Goal:** Optimize program execution by reducing inter-zone qubit movements.



Figure: Execution time breakdown on zoned architectures.

# Mantra: Key Techniques

**Mantra (Minimizing trAp movemeNts for aTom aRray Architectures)** introduces:

- ▶ **Fountain-Shaped CZ Chain:** Reduces single-qubit gate overhead and cancels intermediate gates..
- ▶ **Preemptive Gate Scheduling:** Executes independent gates earlier to minimize inter-zone transitions.
- ▶ **1Q-Gateless ZZ Interaction:** Replaces CZ-based decompositions with direct Rydberg-mediated ZZ rotations

**Key Idea:** Reduces inter-zone movements and improves overall execution efficiency.

# Fountain-Shaped CZ Chain

► Structure CZ chains around a common qubit.
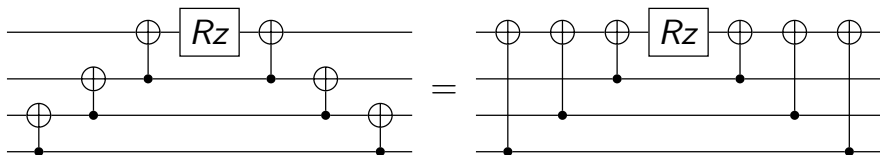


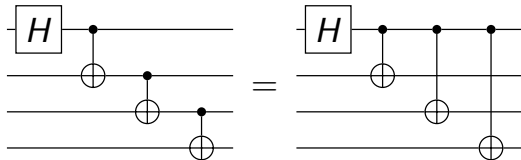Figure: An example Hamiltonian simulation kernel $e^{-i\theta ZZZZ}$



Figure: An example of a 4-qubit GHZ-state circuit.

# Preemptive Gate Scheduling

▶ Identifies independent gates that can be executed earlier in the same zone.

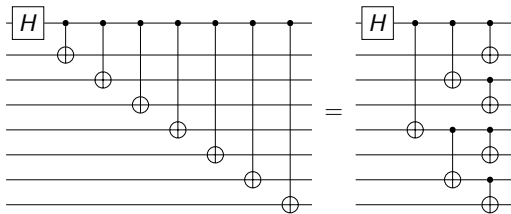▶ Reduces zone-to-zone movements while preserving computation dependencies.



Figure: An example of a 8-qubit GHZ-state circuit.

# 1Q-Gateless ZZ Interaction

▶ **Mantra's approach:** Uses a combination of adiabatic and Levine-Pichler gates to achieve direct ZZ rotations.
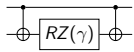
$$
\begin{array}{c}
\vdots \\
\boxed{RZ(\gamma)} \\
\vdots
\end{array}
=
LP(\gamma) =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & e^{-i\gamma} & 0 & 0 \\
1 & 0 & e^{-i\gamma} & 0 \\
1 & 0 & 0 & e^{2\gamma+\pi}
\end{bmatrix}
Ad(\phi_1, \phi_2) =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
1 & 0 & 1 & 0 \\
1 & 0 & 0 & e^{\phi_2-2\phi_1}
\end{bmatrix}
$$

Figure: The proposed arbitrary ZZ rotation protocol consisting of a single adiabatic (Ad) and a single Levine-Pichler (LP) gate, where $\phi_1 = (\pi + 2\gamma + \phi_2)/2$.

# Results: Performance Improvement

| Workloads | Logical Qubits | # of LD/STs (X-basis calculation is allowed.) | | | # of Physical Gates | | | Total Circuit Fidelity | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Standard | Mantra | Reduced | Standard | Mantra | Reduced | Standard | Mantra | Improved |
| GHZ | 40Q | 78 | 10 (8) | 87.2% (89.7%) | 826 | 826 | 0.0% | 0.75 | 0.76 | 1.5% |
| | 80Q | 158 | 2 (0) | 98.7% (100.0%) | 1,666 | 1,666 | 0.0% | 0.56 | 0.57 | 2.6% |
| | 120Q | 238 | 2 (0) | 99.2% (100.0%) | 2,506 | 2,506 | 0.0% | 0.42 | 0.43 | 3.1% |
| PO | 3Q | 36 | 6 | 83.3% | 322 | 259 | 19.6% | 0.89 | 0.89 | 0.9% |
| | 6Q | 180 | 6 | 96.7% | 1,596 | 1,281 | 19.7% | 0.55 | 0.58 | 4.6% |
| | 9Q | 432 | 6 | 98.6% | 3,808 | 3,052 | 19.8% | 0.24 | 0.27 | 11.4% |
| QNN | 8Q | 46 | 16 | 65.2% | 959 | 567 | 40.9% | 0.68 | 0.71 | 5.8% |
| | 16Q | 94 | 32 | 66.0% | 3,731 | 2,051 | 45.0% | 0.21 | 0.27 | 28.6% |
| | 24Q | 142 | 48 | 66.2% | 8,295 | 4,431 | 46.6% | 0.03 | 0.11 | 73.7% |
| UCC | 5Q | 160 | 40 | 75.0% | 1,680 | 707 | 57.9% | 0.57 | 0.65 | 14.9% |
| | 10Q | 360 | 40 | 88.9% | 3,780 | 1,407 | 62.8% | 0.28 | 0.40 | 40.0% |
| | 15Q | 560 | 40 | 92.9% | 5,880 | 2,107 | 64.2% | 0.14 | 0.24 | 71.5% |
| VR | 15Q | 84 | 84 | 0.0% | 910 | 588 | 35.4% | 0.74 | 0.78 | 4.7% |
| | 30Q | 174 | 174 | 0.0% | 1,855 | 1,218 | 34.3% | 0.54 | 0.59 | 9.7% |
| | 45Q | 264 | 264 | 0.0% | 2,800 | 1,848 | 34.0% | 0.39 | 0.45 | 14.6% |
| Geometric Mean | | 153.6 | 20.6 (18.5) | 86.6% (87.9%) | 2,010.1 | 1,297.8 | 35.4% | 0.37 | 0.43 | 17.1% |

Figure: Mantra reduces inter-zone movements by 86.6%, also reduces physical gate counts by 35%, improving overall fidelity by 17%

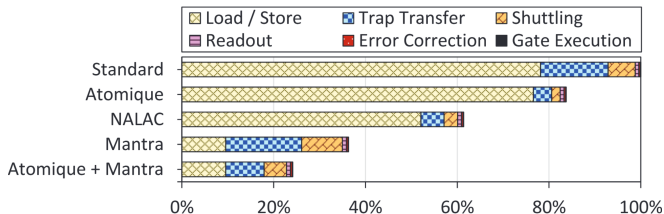# Execution Breakdown According to Compiler



Figure: Execution time breakdown analysis. Combining Atomique and Mantra could further enhance the performance of zoned architectures.

# Conclusion

- Zoned neutral atom architectures have high gate fidelities but suffer from slow qubit movement.
- Mantra optimizes execution by restructuring gate sequences and minimizing zone transfers.
- Results demonstrate significant reductions in execution time and improved fidelity.