Introduction to Willow

The newest generation of superconducting processors from Google Quantum AI

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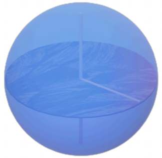
January 8, 2025

Google’s quantum computing roadmap

Our focus is to unlock the full potential of quantum computing by developing a large-scale computer capable of complex, error-corrected computations. We're guided by a roadmap featuring six milestones that will lead us toward top-quality quantum computing hardware and software for meaningful applications.

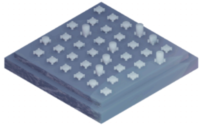


MILESTONE 1

BEYOND CLASSICAL

Physical Qubits: 54
Logical Qubit Error Rate: -

2019

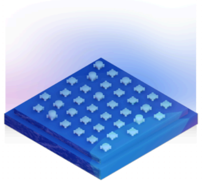


MILESTONE 2

QUANTUM ERROR CORRECTION

Physical Qubits: 10^2
Logical Qubit Error Rate: 10^{-2}

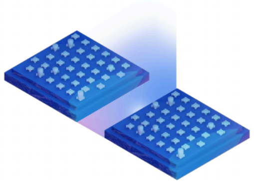
2023



MILESTONE 3

BUILDING A LONG-LIVED LOGICAL QUBIT

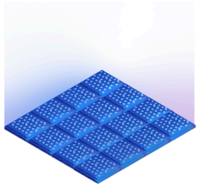
Physical Qubits: 10^3
Logical Qubit Error Rate: 10^{-6}



MILESTONE 4

CREATING A LOGICAL GATE

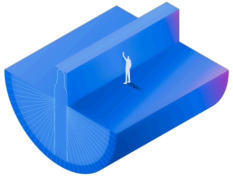
Physical Qubits: 10^4
Logical Qubit Error Rate: 10^{-6}



MILESTONE 5

ENGINEERING SCALE UP

Physical Qubits: 10^5
Logical Qubit Error Rate: 10^{-6}

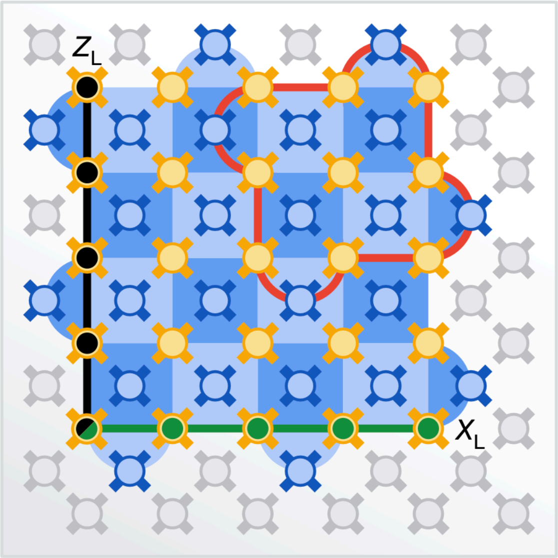


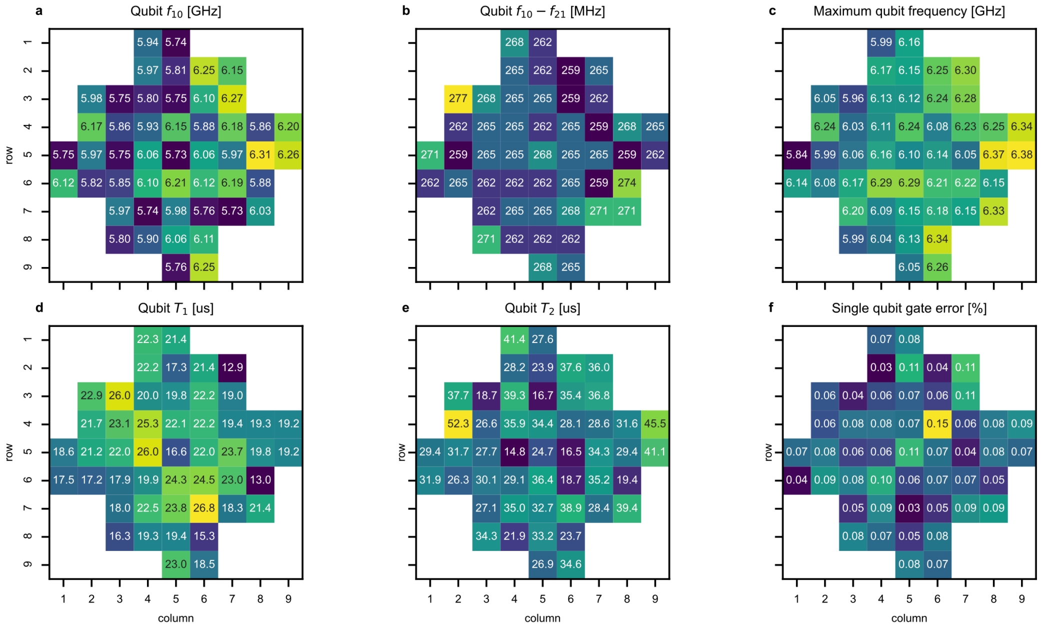
MILESTONE 6

LARGE ERROR-CORRECTED QUANTUM COMPUTER

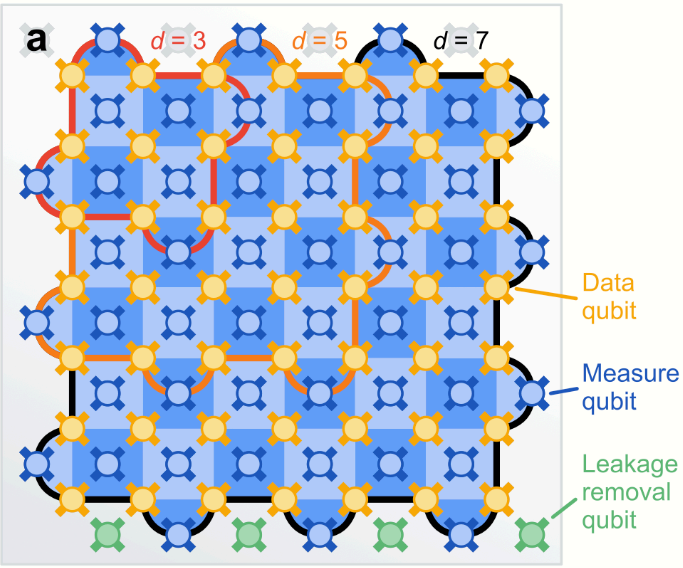
Physical Qubits: 10^6
Logical Qubit Error Rate: 10^{-13}

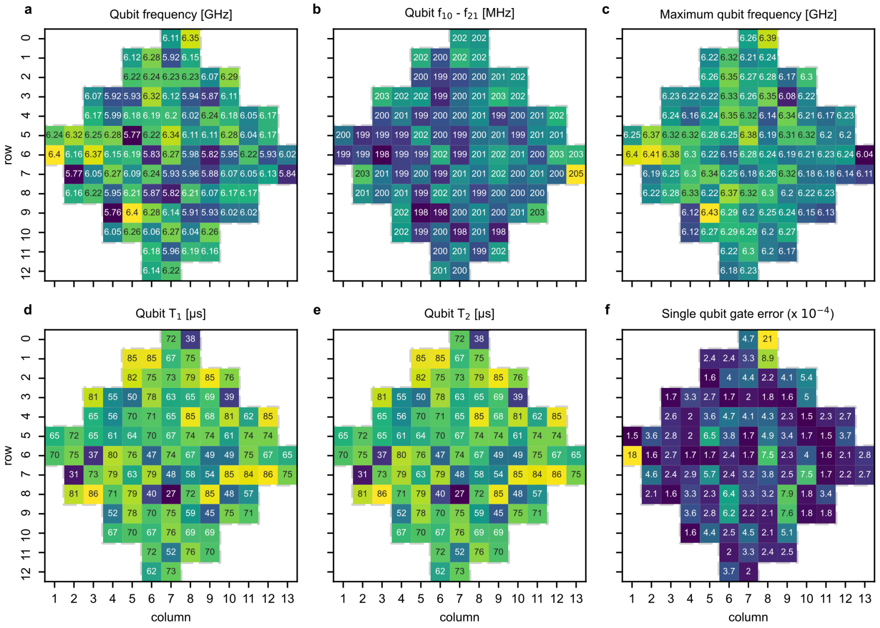
Sycamore (72 qubits, 2022)



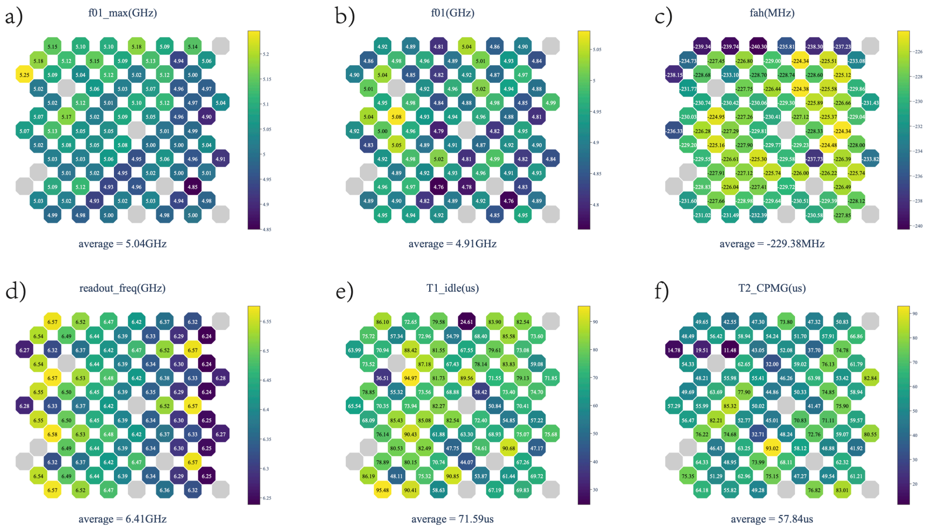


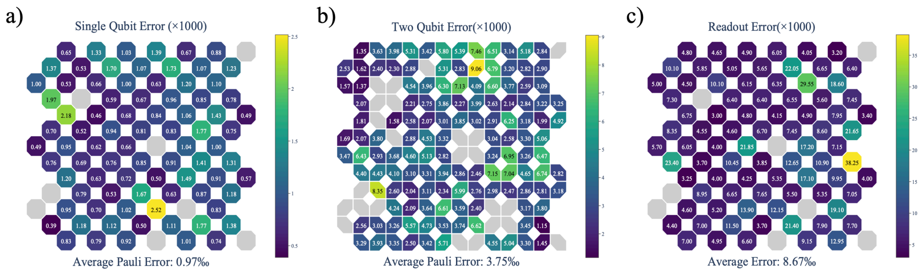
Willow (105 qubits, 2024)



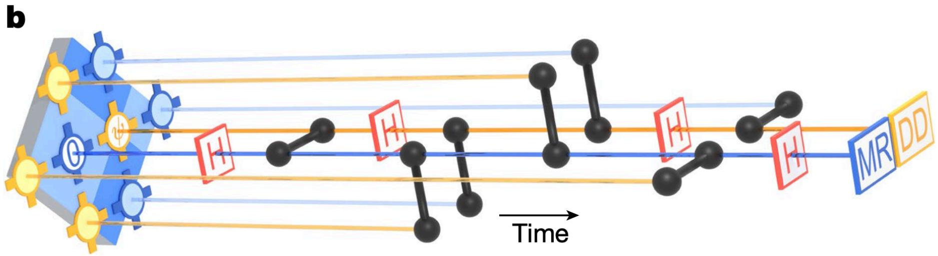


Zuchongzhi 3.0 (105 qubits, 2024)





Surface code circuits

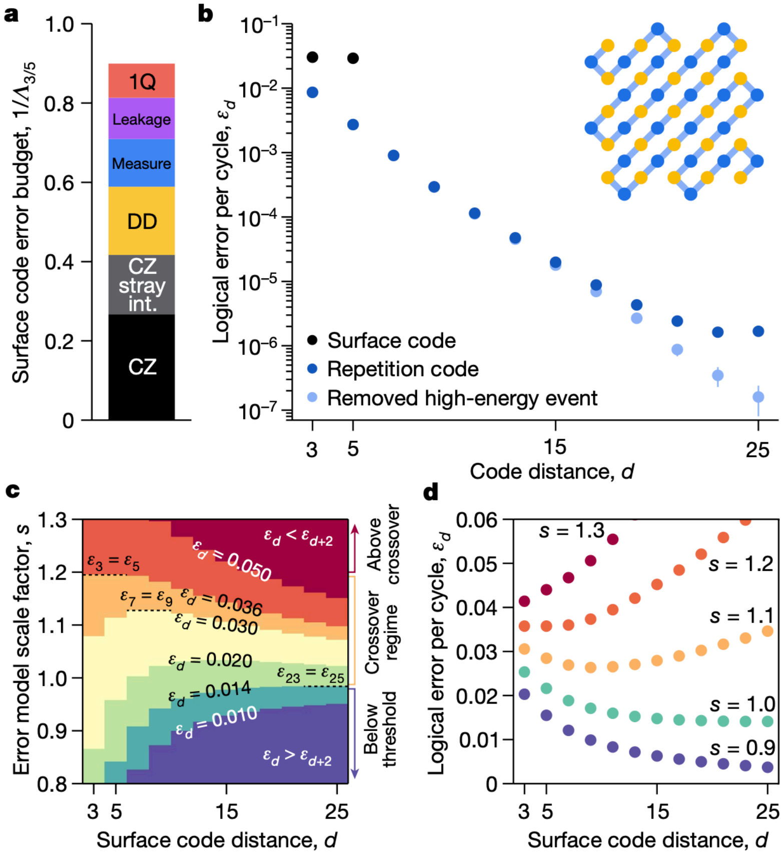


A stabilizer measurement. MR: measure and reset, DD: dynamical decouple

- Prepare **data qubits** in a product state in either the X_L or Z_L basis of the ZXXZ surface code
- **Measure qubits** extract parity information from the data qubits to be sent to the **decoder**
- Repeat a variable number of cycles of error correction
- Run **data qubit leakage removal (DQLR)** to ensure that leakage is short-lived
  - Add special SWAP gates
  - See Overcoming leakage in quantum error correction. *Nature Physics* **19**, 1780–1786 (2023)
- Measure the state of the **logical qubit** by checking decoder's outcome

Threshold

- In principle, as physical error rates decrease, the logical error rate of a larger code should improve faster than a smaller code
  - See 3-logical-errors.ipynb
- But leakage accumulation etc. may cause larger code performance to degrade faster
- Logical error rate: $\varepsilon_d \propto \left(\frac{p}{p_{\text{thr}}}\right)^{(d+1)/2}$
  - p: physical error rate
  - p_{thr}: threshold error rate
- Error suppression factor: $\Lambda = \frac{\varepsilon_d}{\varepsilon_{d+2}}$



Sycamore (72 qubits)

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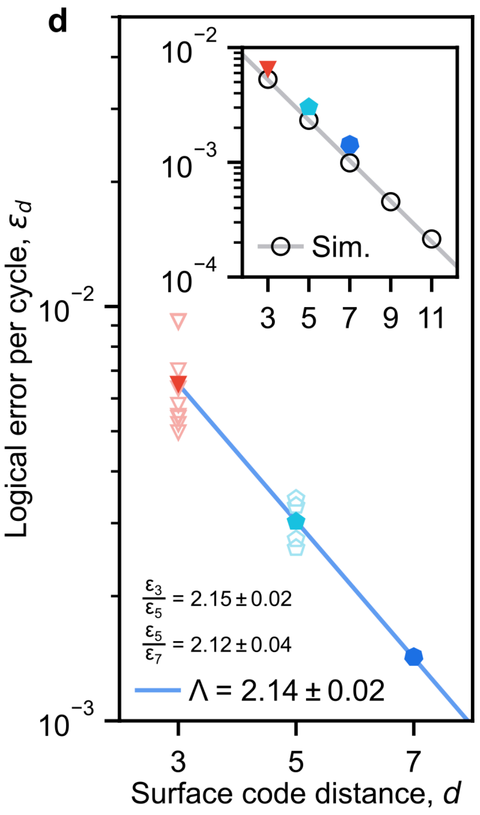
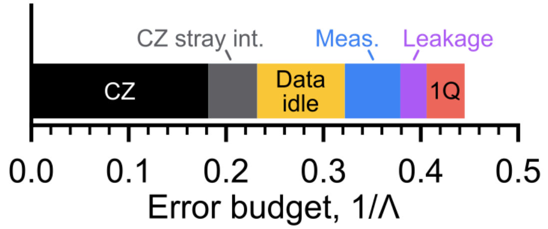


Willow (105 qubits)

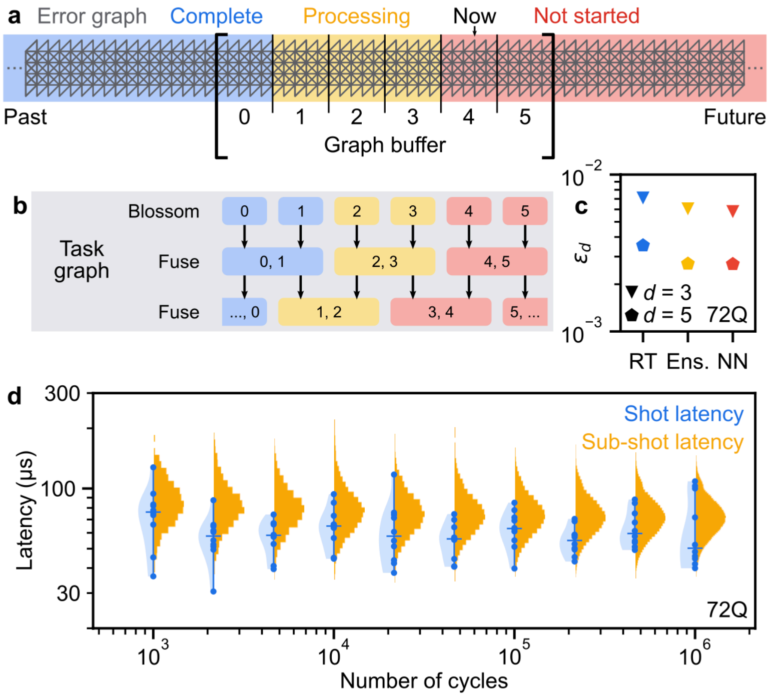
Error budget

Component	$p_{\mathrm{expt}}^{(i)}$	w_i	$1/\Lambda$ **contrib.**
CZ gates	2.8×10^{-3}	65	0.182 (41%)
CZ crosstalk	5.5×10^{-4}	91	0.05 (11%)
CZ leakage	2.0×10^{-4}	108	0.022 (5%)
Data qubit idle	0.9×10^{-2}	10	0.09 (20%)
Readout	0.8×10^{-2}	6	0.048 (11%)
Reset	1.5×10^{-3}	6	0.009 (2%)
SQ gates	6.2×10^{-4}	63	0.039 (9%)
Leakage (heating)	2.5×10^{-4}	18	0.005 (1%)



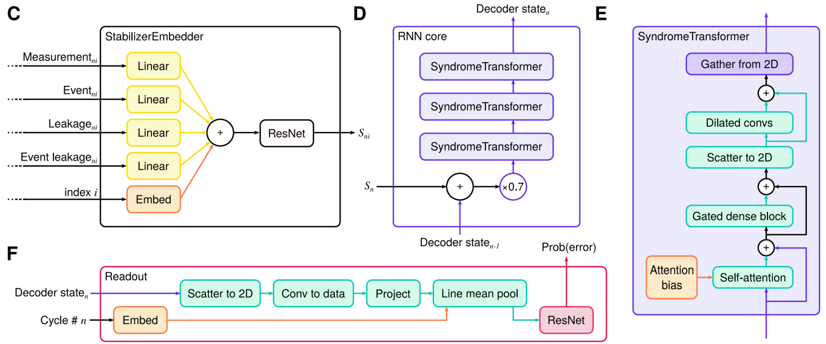
Real-time decoding (1)

- Streaming decoding algorithm
  - Subdivided into blocks, with different threads responsible for different blocks
- Sparse Blossom algorithm
  - Resolve local configurations of errors, using a parallelization strategy
- Real-time vs offline
  - Performance metrics: accuracy, latency and throughput
  - Average latency: 63±17 μs
  - Real-time decoder vs neural network: 20 times faster



Real-time decoding (2)

- List of decoders:
  - Neural network decoder
  - Matching synthesis decoder *Libra*
  - Ensembled matching decoder *Harmony*
  - Correlated matching decoder
  - Real-time decoder
  - Beliefmatching, BP+OSD, and tensor network decoders, etc.



References

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- Google Quantum AI. Suppressing quantum errors by scaling a surface code logical qubit. *Nature* 614, 676–681 (2023).
- Google Quantum AI. Exponential suppression of bit or phase errors with cyclic error correction. *Nature* 595, 383–387 (2021).
- USTC Quantum Group and Collaborators. Establishing a New Benchmark in Quantum Computational Advantage with 105-qubit *Zuchongzhi* 3.0 Processor, arXiv:2412.11924 (2024)
- Google Quantum AI