Exploring Quantum Error Reduction with Amazon Braket

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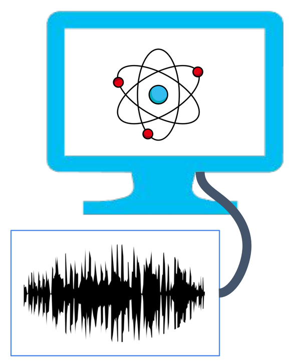
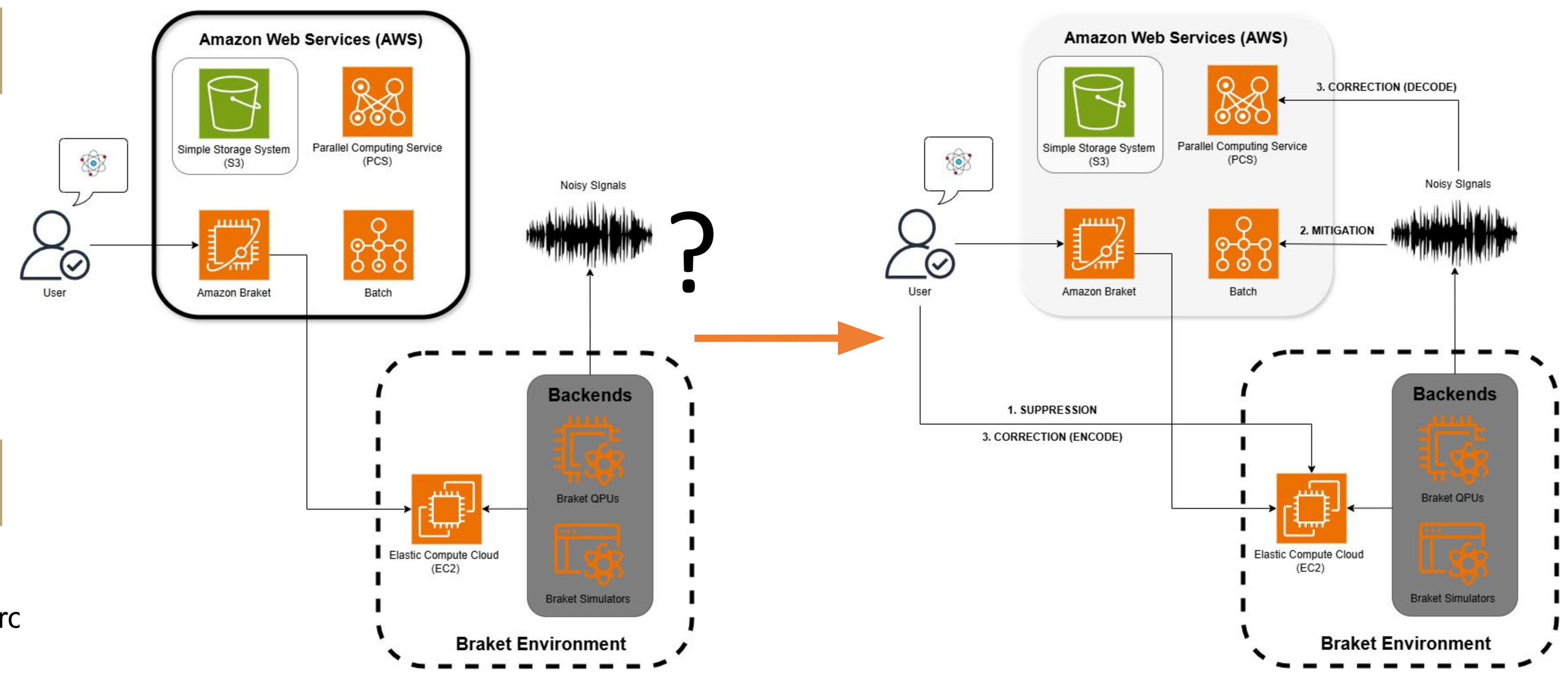
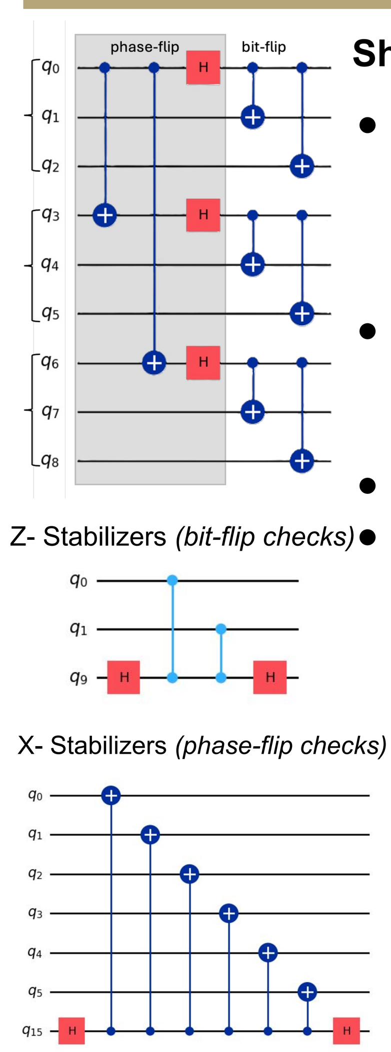
Motivation and Background

- **Motivations:** Quantum computers are highly sensitive to noise and decoherence, making error reduction essential for reliable quantum computation.
- This project explores **error suppression, error mitigation, and error correction techniques** using Amazon Braket and AWS computational resources, demonstrating practical workflows for scalable quantum simulations and quantum hardware interfacing.



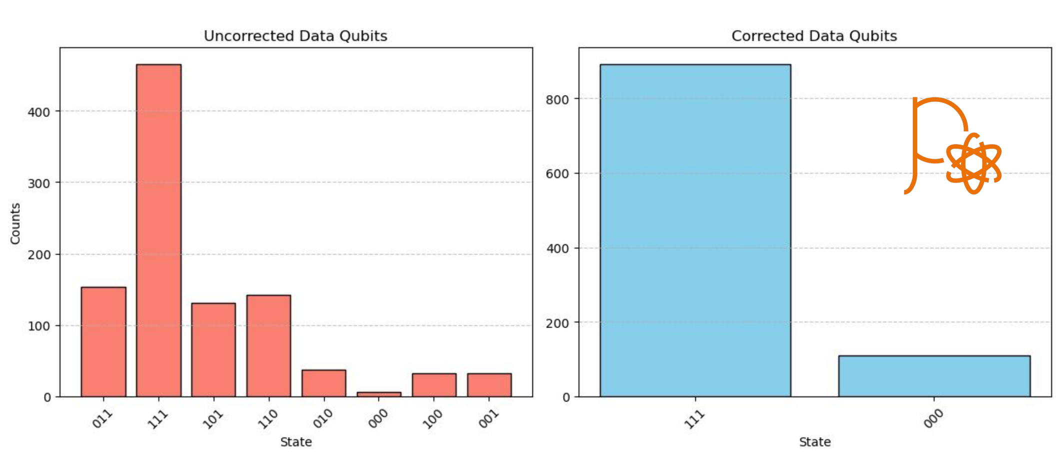


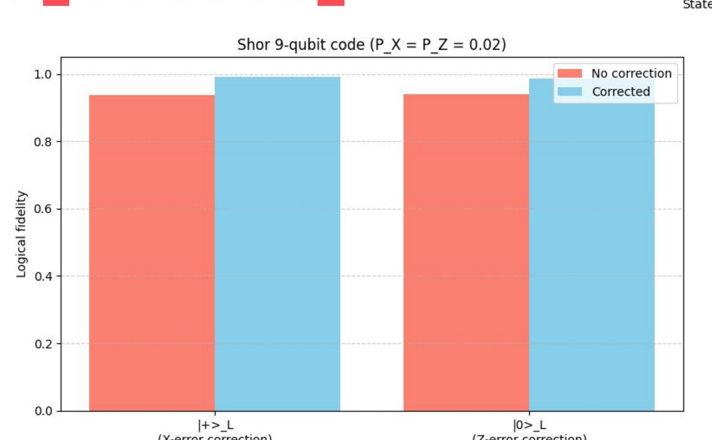
Error Correction

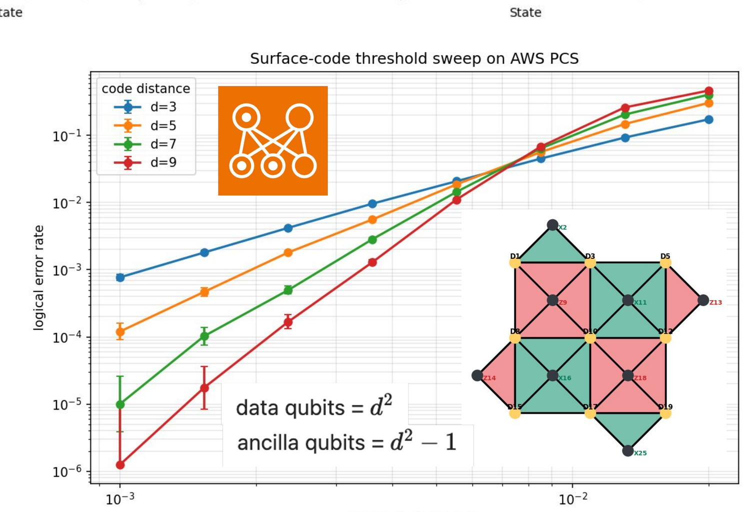


Shor Code Simulation

- **Concept:** 9-qubit stabilizer code protecting one logical qubit frc single-qubit errors: *bit-flip, phase-flip, and both*. Stabilizer measurements detects errors. The circuit uses 9 data qubits and 8 ancilla qubits.
- **Workflow:** State preparation, concatenated encoding, error injection, 8 stabilizer syndrome measurements, density-matrix simulation, and classical decoding.
- **Tools:** Amazon Braket with the DM1.
- **Results:** Logical-state recovery under selected error channels.







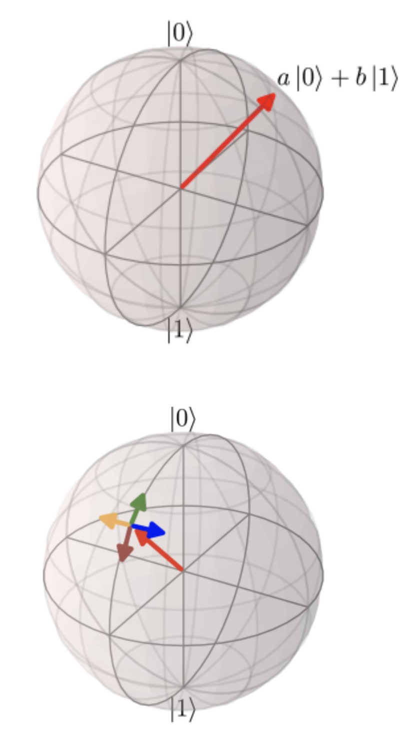
Surface Code Simulation

- **Concept:** Hardware-efficient code using local X- and Z-type stabilizers on a 2D lattice. Scalability is achieved via nearest-neighbor (NN) interactions that simplify hardware routing. Errors are detected as syndrome defects and decoded by matching.
- **Workflow:** Stabilizer circuits, repeated syndrome extraction, and classical decoding.
- **Tools:** *Stim* for fast stabilizer simulation, *PyMatching* for decoding, and AWS PCS for parallel HPC runs.
- **Results:** increasing the code distance (d) suppresses the logical error rate when the physical error rate is below the threshold.

Error Suppression

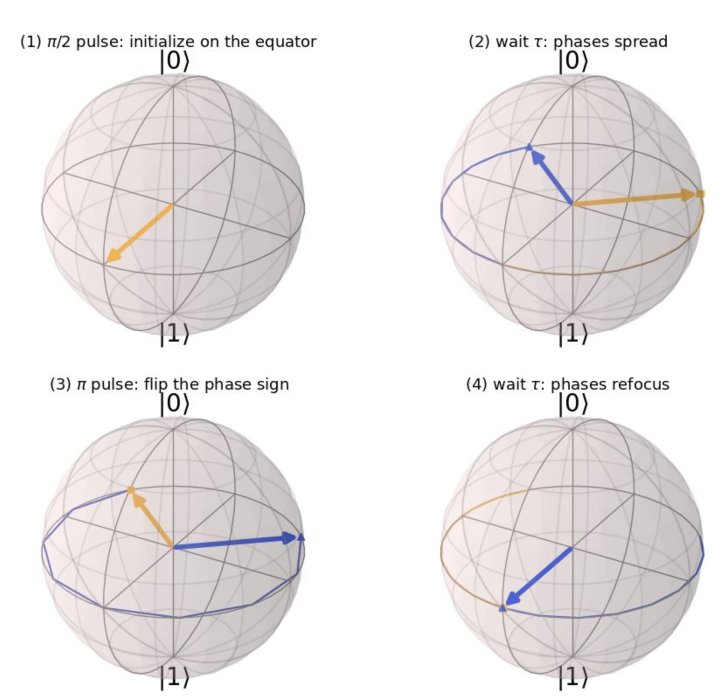
Qubit characterization: T_1, T_2 and T_2^*

- **T_1, T_2 and T_2^*** are key timescales that describe how long a physical qubit can preserve quantum information
- **T_1** measures how long a qubit can remain in |0⟩ or |1⟩ before energy relaxation changes its state
- **T_2 and T_2^*** measure how long a qubit preserves the relative phase of a superposition. T_2^* includes intrinsic dephasing plus slow frequency noise. T_2 is the intrinsic dephasing time measured after refocusing the slow noise.

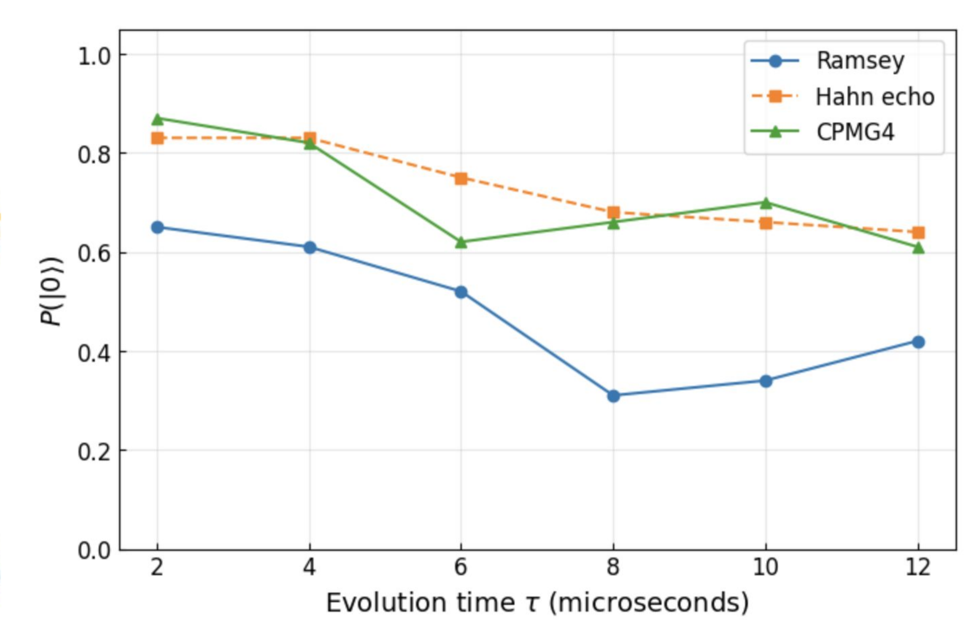


Error suppression on the hardware level: dynamical decoupling

- **Method:** Apply a sequence of control pulses to cancel part of the slow environmental noise.
- **Commonly used sequences:** Hahn echo and Carr-Purcell-Meiboom-Gill (CPMG)



Pulse sequence of Hahn echo

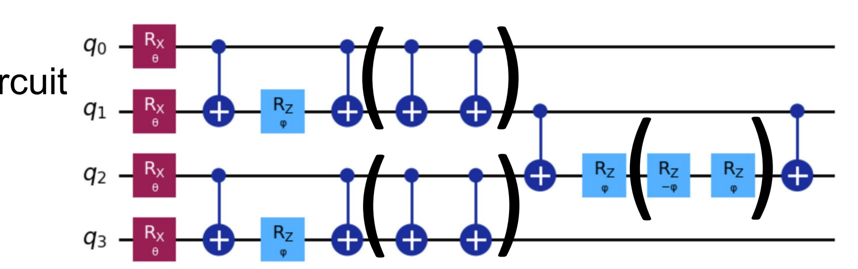


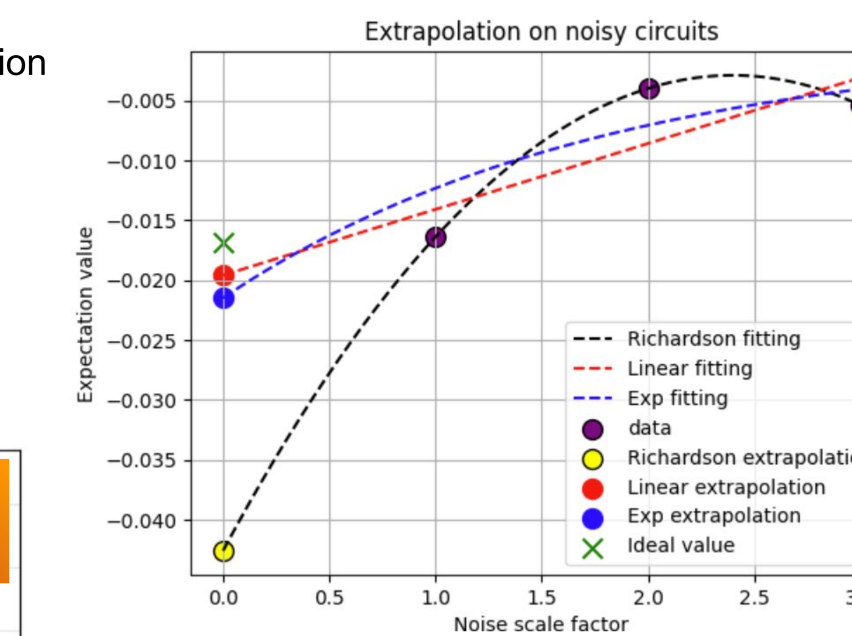
- **Result:** Hahn echo and CPMG maintain a higher |0⟩ population than Ramsey at long evolution times. This shows that dynamical decoupling suppresses slow dephasing noise and helps preserve qubit coherence.

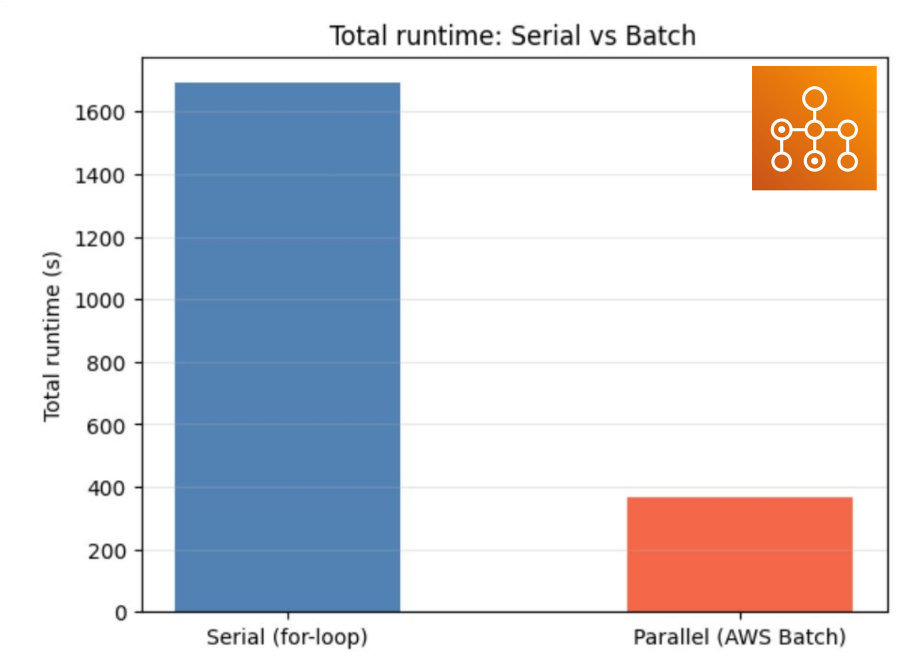
Error Mitigation

Zero-Noise Extrapolation

- **Concept:** Extrapolate the ideal quantum circuit performance from outcomes of the scaled noise circuits.
- **Workflow:** Build up circuits for ideal and scaled-noise 1D Ising model simulations. Extrapolate the results through the expectation values of the scaled-noise circuits.
- **Tools:** Amazon Braket with the DM1 density-matrix simulator.
- **Results:** Demonstrates zero-noise extrapolation with different methods and compare to the ideal values.







AWS Batch

- **Theory/Tools:** Get access to AWS Batch computation resources to accelerate the simulations.
- **Workflow:** Build up circuits for each discrete time steps and upload to Batch. Retrieve data.
- **Results:** Save 75% of the time for simulations with AWS Batch on heavy loading tasks.

Summary

- We implemented and analyzed **dynamical decoupling, zero-noise extrapolation**, and quantum error correction protocols including **the Shor and surface codes**.
- Our results demonstrate improved coherence recovery, reduced simulation error, and logical error suppression below the fault-tolerance threshold.
- This work also highlights how Amazon Braket integrates quantum hardware, simulators, and scalable cloud resources for quantum computing research and education.

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