Quantum Walks & Monte Carlo Project

WISER 2025 x NNL

Team Name: Quantum Probability Pioneers

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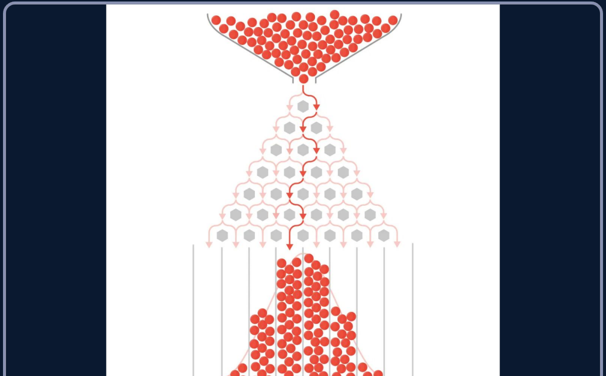
Problem Statement

This project explores how **quantum circuits can simulate complex systems** through a Galton Box-style Monte Carlo problem.

The challenge addresses high-dimensional problems with complex interactions such as:

- Particle transport simulations
- Quantum systems modeling
- PDE solutions for complex interactions

Based on the **Universal Statistical Simulator**, we implement quantum circuits to simulate a Galton Box (Plinko) game, leveraging the Quantum Fourier Transform for potential exponential speed-up over classical methods.



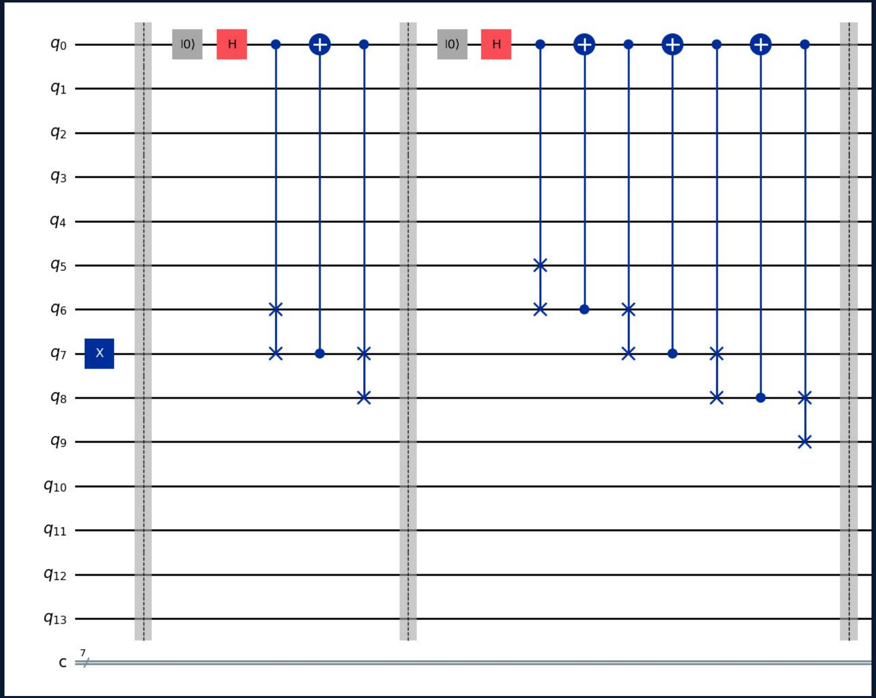
Approach & Objectives

Our approach leverages **quantum circuit design** to simulate the Galton Box problem as a quantum walk.

Project Objectives:

- Implement quantum Galton boards using quantum circuits
- Create a general algorithm for any number of layers
- Generate different target distributions (Gaussian, Exponential, Hadamard)
- Optimize for real hardware noise models

We utilize **Qiskit** with an all-to-all sampler for noiseless quantum simulations, focusing on maximizing accuracy and board layers.



Quantum Galton Board Circuit (Partial)

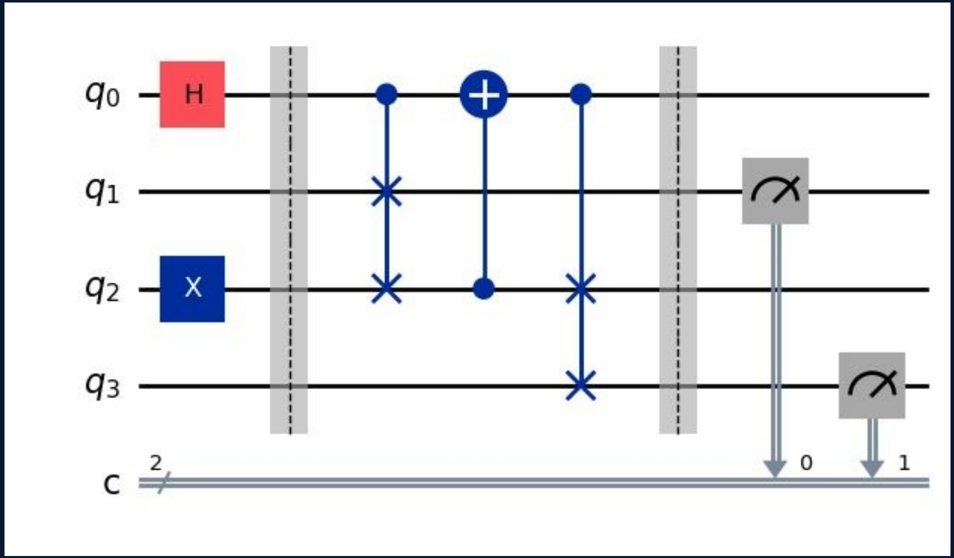
Evolution & Implementation

Our implementation evolved from basic 1-2 layer models to a **generalized n-layer algorithm** for quantum Galton boards.

Key implementation features:

- Parameterized circuit generation for any number of layers
- Modified quantum gates to achieve different distributions
- Noise mitigation techniques for hardware implementation
- Optimized circuits using Qiskit transpiler with optimization level 3

```
# Pseudocode for n-layer Galton Box
def create_quantum_galton(n_layers):
 # Initialize quantum circuit
 # Apply layer-specific gates
 # Measure and return distribution
```



Quantum Peg Circuit

Methodology & Evaluation

We evaluated our quantum circuits on **12 different IBM fake backends** with qubit capacities ranging from 127-156.

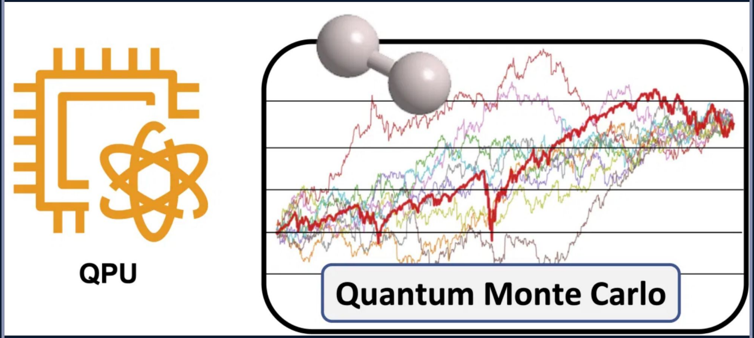
Evaluation Metrics:

- Total Variation Distance
- Jensen-Shannon Divergence
- 1D Wasserstein Distance

Optimization:

- Qiskit transpiler with optimization level 3
- Circuit depth optimization
- Noise model adaptation

The **Torino backend** consistently provided the best results across Gaussian and Hadamard distributions.



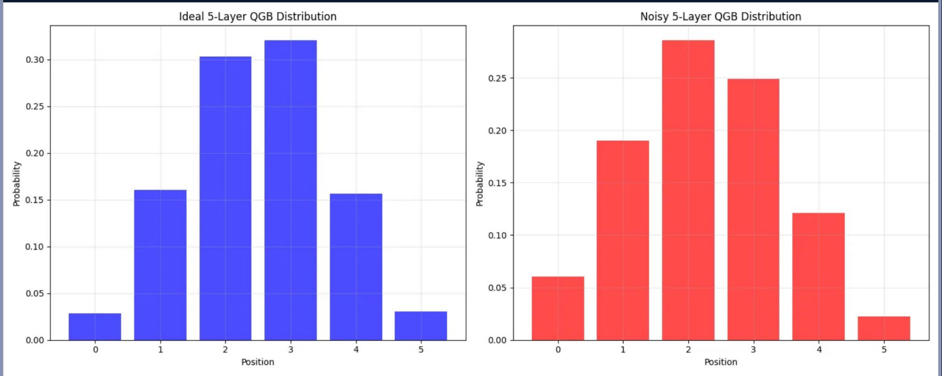
Quantum Monte Carlo Simulation

Gaussian Distribution Results (Torino Backend)

We evaluated the Gaussian distribution on various IBM fake backends, with the **Torino backend** yielding the best results.

The circuit was optimized using Qiskit transpiler with optimization level 3.

Metric	Value
Total Variation Distance	0.0965
Jensen-Shannon Divergence	0.1023
1D Wasserstein Distance	0.2277
Original Circuit Depth	67
Transpiled Circuit Depth	777



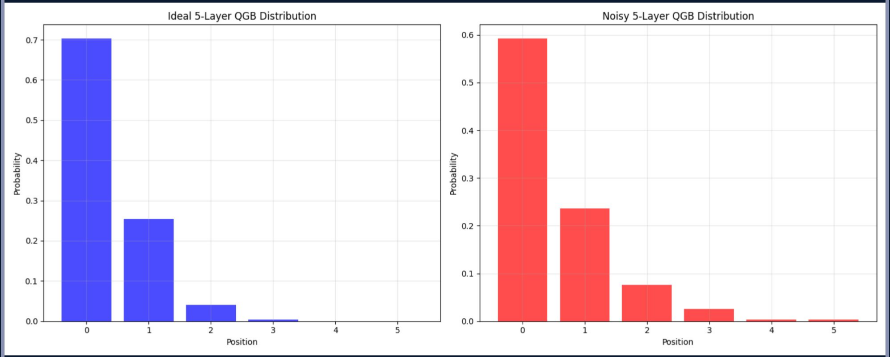
Ideal vs Noisy Gaussian Distribution (Torino Backend)

Exponential Distribution Results (Cusco Backend)

We evaluated the Exponential distribution on various IBM fake backends, with the **Cusco backend** yielding the best results.

The circuit was optimized using Qiskit transpiler with optimization level 3.

Metric	Value
Total Variation Distance	0.0954
Jensen-Shannon Divergence	0.1318
1D Wasserstein Distance	0.4688
Original Circuit Depth	67
Transpiled Circuit Depth	777



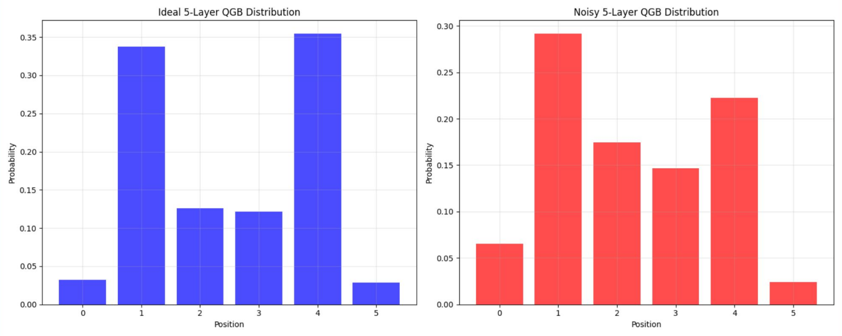
Ideal vs Noisy Exponential Distribution (Cusco Backend)

Hadamard Distribution Results (Torino Backend)

We evaluated the Hadamard distribution on various IBM fake backends, with the **Torino backend** yielding the best results.

The circuit was optimized using Qiskit transpiler with optimization level 3.

Metric	Value
Total Variation Distance	0.1443
Jensen-Shannon Divergence	0.1414
1D Wasserstein Distance	0.2129
Original Circuit Depth	67
Transpiled Circuit Depth	777



Ideal vs Noisy Hadamard Distribution (Torino Backend)

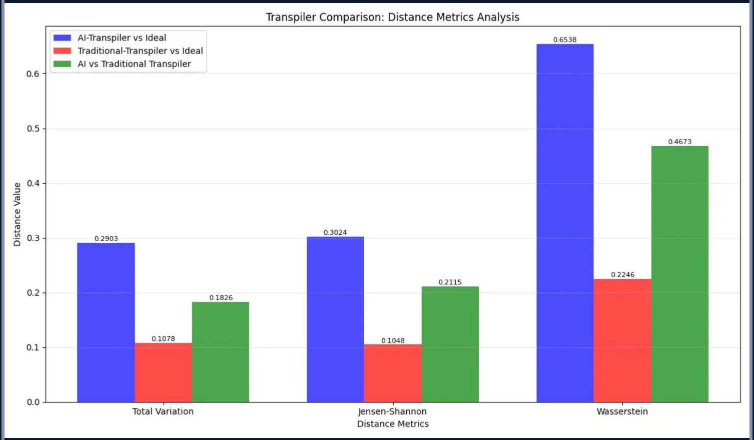
AI-Transpiler Experiment Results

We explored the impact of Qiskit's experimental **AI-transpiler** on circuit performance for Gaussian distributions on the Torino and Cusco backends.

Torino Backend Results

Metric	AI vs Ideal	Traditional vs Ideal
Total Variation Distance	0.2903	0.1078
Jensen-Shannon Divergence	0.3024	0.1048

The AI-transpiler did not show improvement over traditional transpilation in our experiments.



AI vs. Traditional Transpiler Performance

Future Scope

Building on our current implementation, several promising directions for future work include:

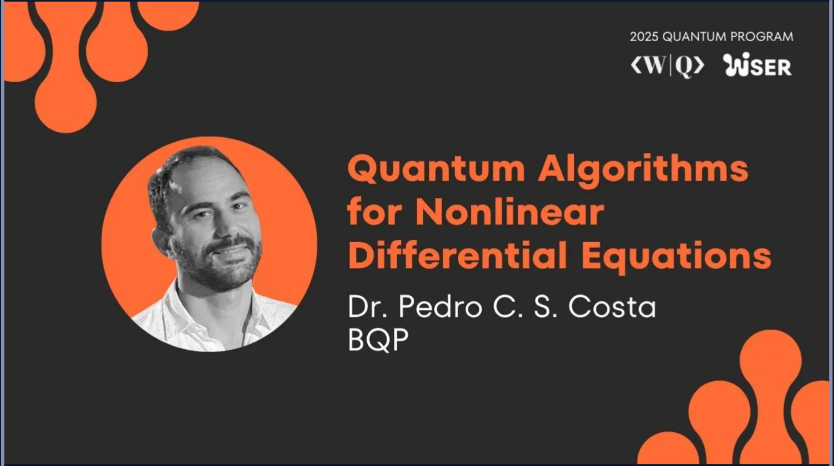
Extensions

- Higher-dimensional quantum walks
- Integration with quantum machine learning
- Application to specific PDE problems

Limitations

- Circuit depth (current: 46)
- Coupling map constraints
- Noise impact on distribution fidelity

To advance further, we would need **improved error correction techniques** and **higher qubit connectivity** in quantum hardware.



Broader Context of Quantum Walks Research

Thank You

Quantum Walks & Monte Carlo Project

Team: Quantum Probability Pioneers

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GitHub: https://github.com/KaziMuktadirAhmed/WISER-womenium-2025-project-1

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