# Project Documentation for Quantum Walks and Monte Carlo *by Team BiasQ*

# Introduction & Problem Statement

This project implements quantum circuits to simulate **Galton board–style particle walks**, combining Quantum Walks with Monte Carlo techniques. Our motivation lies in addressing the computational limitations of classical Monte Carlo methods for high-dimensional simulations, such as particle transport and diffusion. Classical simulations often scale poorly with system size and dimensionality, whereas quantum walks offer a potential pathway to achieve quadratic or even exponential speed-ups. By extending the work to include noise-aware optimization and statistical distance analysis, we not only met the challenge requirements but also explored how such quantum algorithms can be made more resilient and practical for real-world applications.

We chose this project out of genuine curiosity to explore the fascinating intersection of **Quantum Walks** and **Monte Carlo methods**, and to challenge ourselves with the more advanced tasks, particularly **Task 4** and **Task 5**. These tasks focus on noise modeling, optimization, and distribution comparison areas closely related to **quantum error mitigation and correction**, which we are deeply passionate about.

## Approach & Methodology

Our approach involved designing parameterized quantum circuits that model the Galton board process using Qiskit. Key steps included:  
- Constructing reusable coin qubits with adjustable bias angles to control step probabilities.  
- Encoding particle positions using one-hot registers for n-layer simulations.  
- Implementing Gaussian, exponential, and Hadamard quantum walk distributions by tuning coin parameters.  
- Running noiseless simulations for baseline results, followed by noise-aware simulations using Aer models (depolarizing, thermal relaxation, and readout noise).  
- Comparing quantum results with classical Monte Carlo baselines using statistical metrics such as Total Variation Distance, Jensen–Shannon Divergence, Wasserstein Distance, and Chi-Square tests.  
- Applying basic error mitigation methods like multi-run averaging and Zero-Noise Extrapolation (ZNE).

## Results & Impact

The project successfully generated quantum distributions matching theoretical targets for Gaussian, exponential, and Hadamard walks. Statistical comparisons demonstrated close agreement with classical baselines in noiseless settings. Under realistic noise, the circuits retained qualitative similarity, though accuracy decreased as expected due to decoherence.  
  
Key achievements:  
- Verified correct distribution shapes using multiple statistical measures.  
- Demonstrated scalable quantum circuit architecture with O(n²) complexity versus O(N·n) for classical Monte Carlo.  
- Established a workflow for designing, simulating, and validating quantum algorithms under realistic noise models.

**Usage of AI**

We used AI (ChatGPT and Gemini) to understand and evaluate few doubts that we had related to the papers we read, content we wrote and grammar while documenting this. Major key prompts were

“This is what I understood, tell me if I missed anything”,

“I am not able to understand this equation explain this like I’m a 14 year old”; “Correct my grammar if I made any mistakes in this paragraph”; And few more asking which structural presentation would be good.

**References:**

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Bordone, P., Buscemi, F., & Bertoni, A. (2005). *Quantum coherent phenomena in semiconductor nanostructures*. *Physica Status Solidi (b)*, 242(1), 262–275. (Discusses Galton board quantum analogies)

IBM Quantum Tutorials – *Quantum Galton Board Simulation using Qiskit*.  
Qiskit Community Tutorials