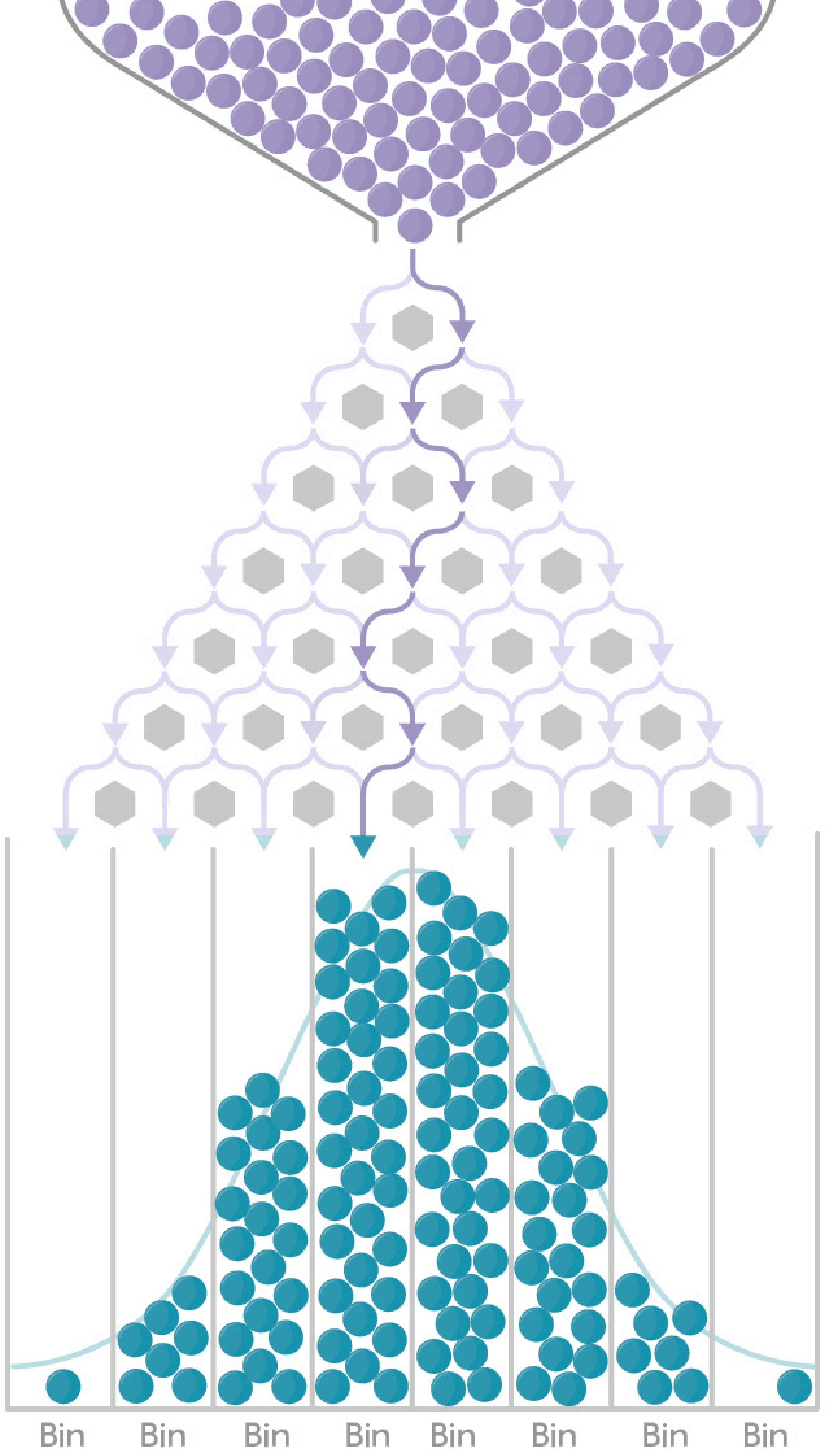
WISER ‹ WOMANIUM | QUANTUM ›

2025 GLOBAL QUANTUM PROGRAM

2025 Quantum Projects

QUANTUM GALTON BOARD



Team: Quantum Walkers

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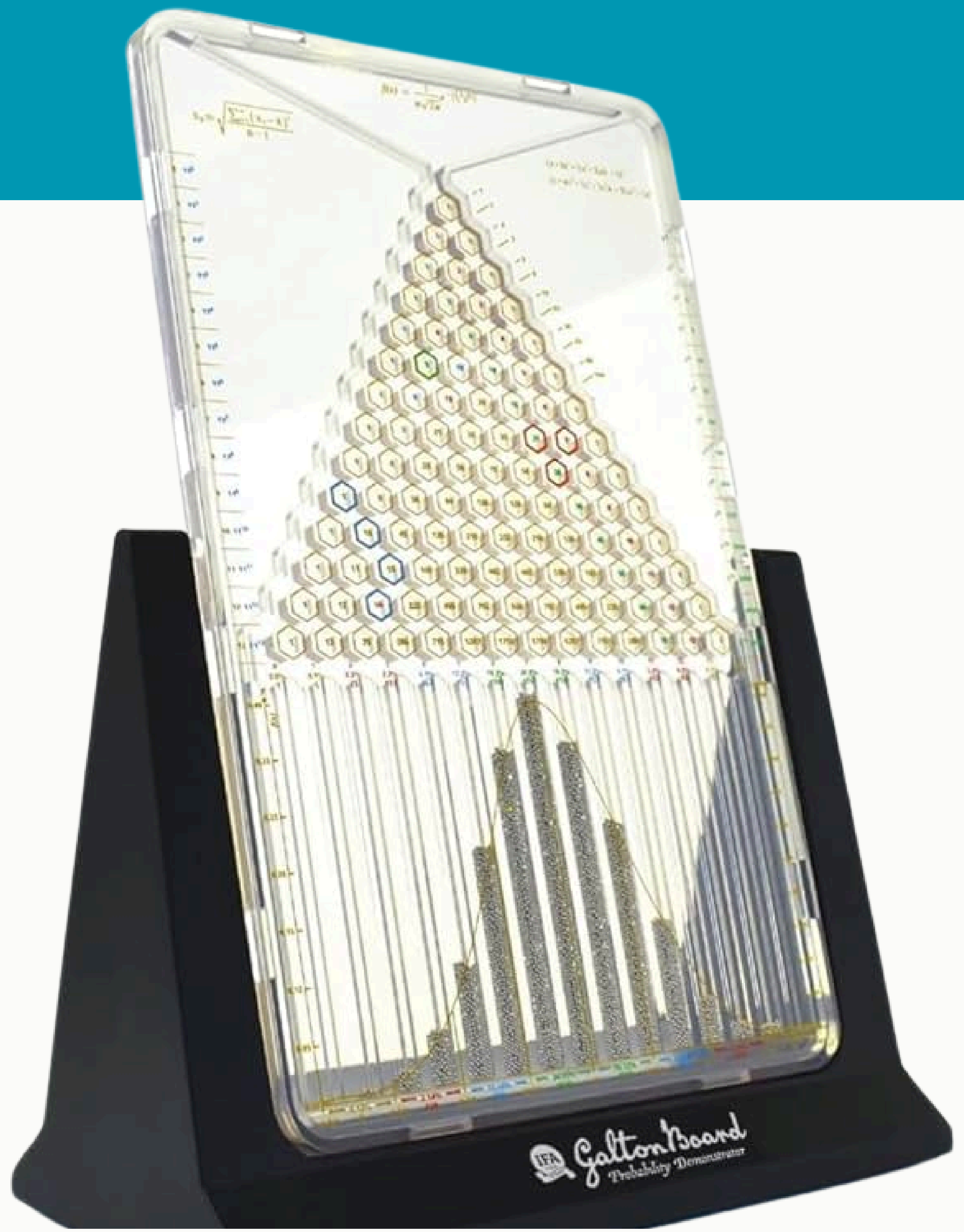
1.Problem Statement



Classical systems like the Galton board simulate random processes through sequential binary decisions, producing well-known statistical distributions such as the Gaussian. However, modeling such systems on classical hardware requires exponential resources as complexity grows.

Can we design a quantum circuit that replicates this statistical behavior more efficiently, using superposition and entanglement to explore all paths simultaneously?

Our challenge is to construct and analyze scalable Quantum Galton Boards that not only simulate classical randomness but also enable generalization to non-Gaussian behaviors under realistic quantum constraints.

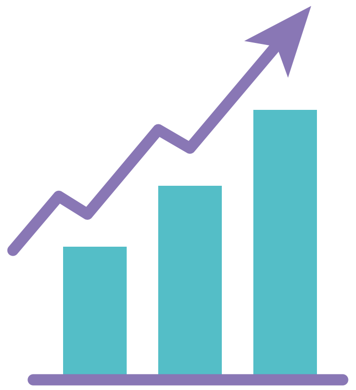
2.Solution

We build a Quantum Galton Board (QGB) in Qiskit using Hadamard and CSWAP gates.

Future Scope

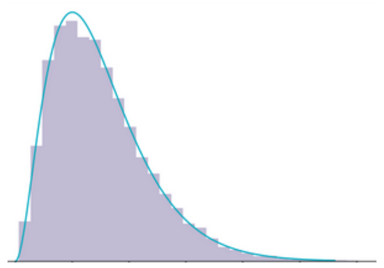
1

Scalable design with qubit reuse for n levels



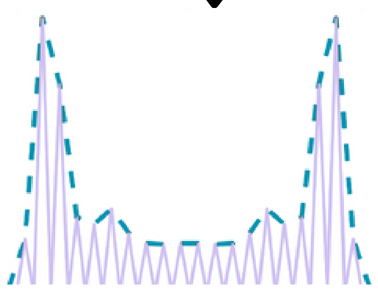
2

Implemented two modified distributions:



Exponential bias

(depth-dependent rotation).

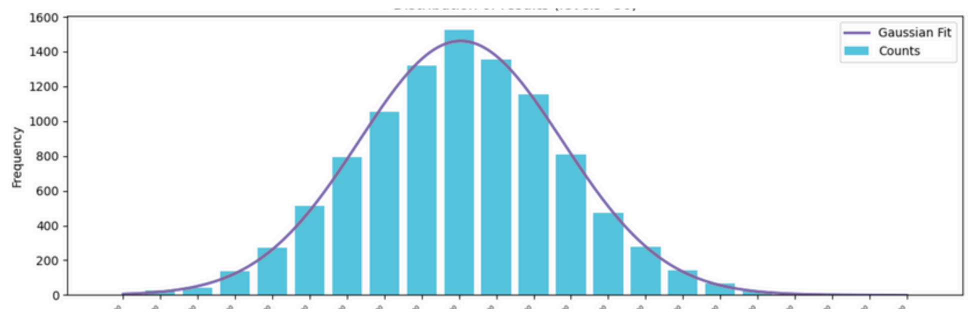


Hadamard quantum walk

(bimodal output).

3

Validated outputs via histograms and compared with targets.



The Quantum Galton Board (QGB) was implemented in Qiskit and executed on Google Colab using the AerSimulator backend with the Matrix Product State (MPS) method, optimizing memory and execution time for low-entanglement circuits.

Two modular functions were defined:

apply_peg

Implements a partial peg using

$$\mathrm{CSWAP}(q_c, q_a, q_b) \rightarrow \mathrm{CNOT}(q_b, q_c)$$

build_level

Stacks k pegs, resetting and reusing the control qubit at each level. The total qubit count is:

$$Q_{\text{total}} = 2n + 2$$

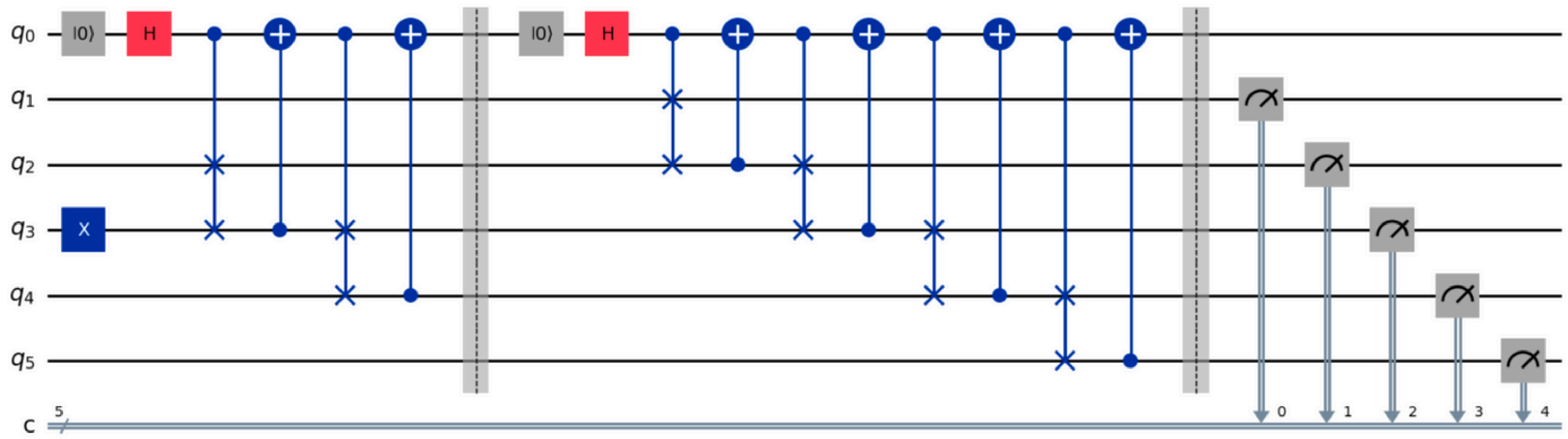


Figure 1: *Quantum circuit implementation of a 2-level Quantum Galton Board composed of 3 quantum pegs. It was made with the code presented in the section "Scaling the QGB to n levels" for n = 2. We can see that it uses an extra CNOT at the end of each level.*

3.2 Unbiased QGB Distribution

The unbiased Quantum Galton Board (QGB) was simulated for n=30 levels using Qiskit's AerSimulator with the matrix product state (MPS) method on Google Colab with NVIDIA Tesla T4 acceleration.

The circuit was executed 10,000 shots, producing the output distribution

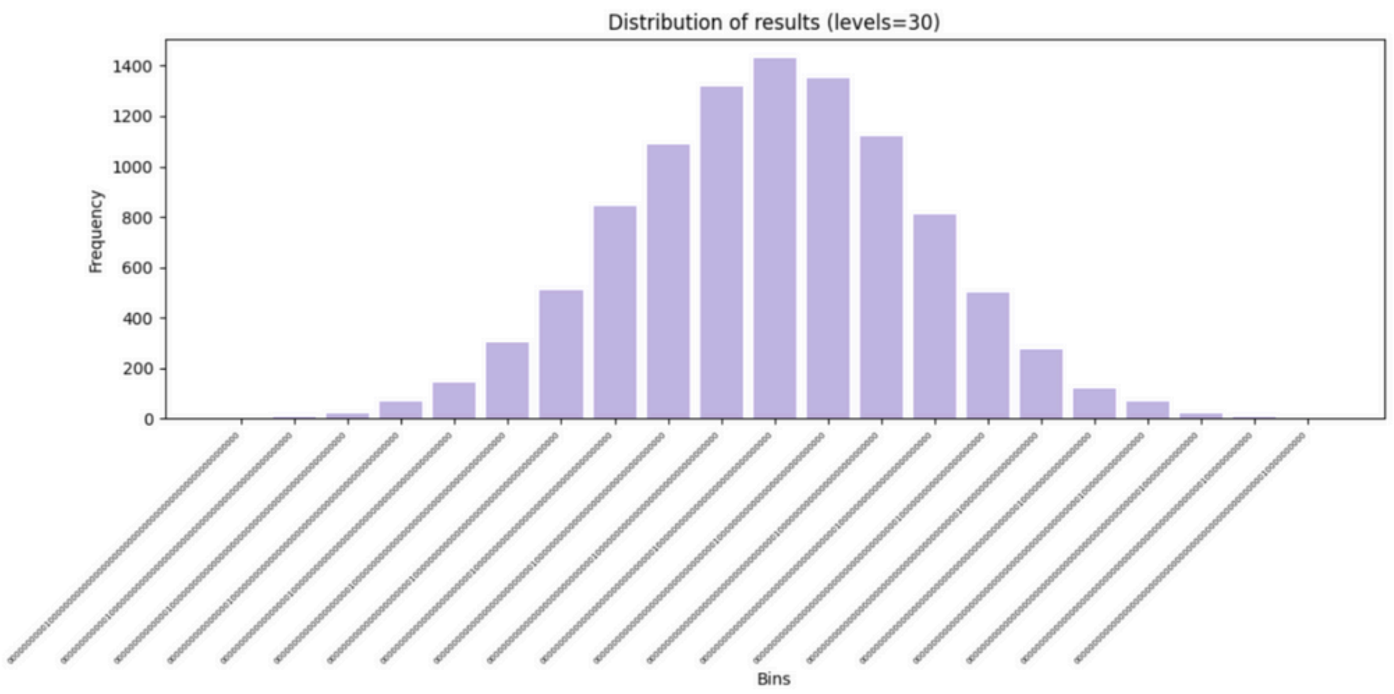


Figure 2: *Output results from the simulation of the 30 levels of QGB circuit.*

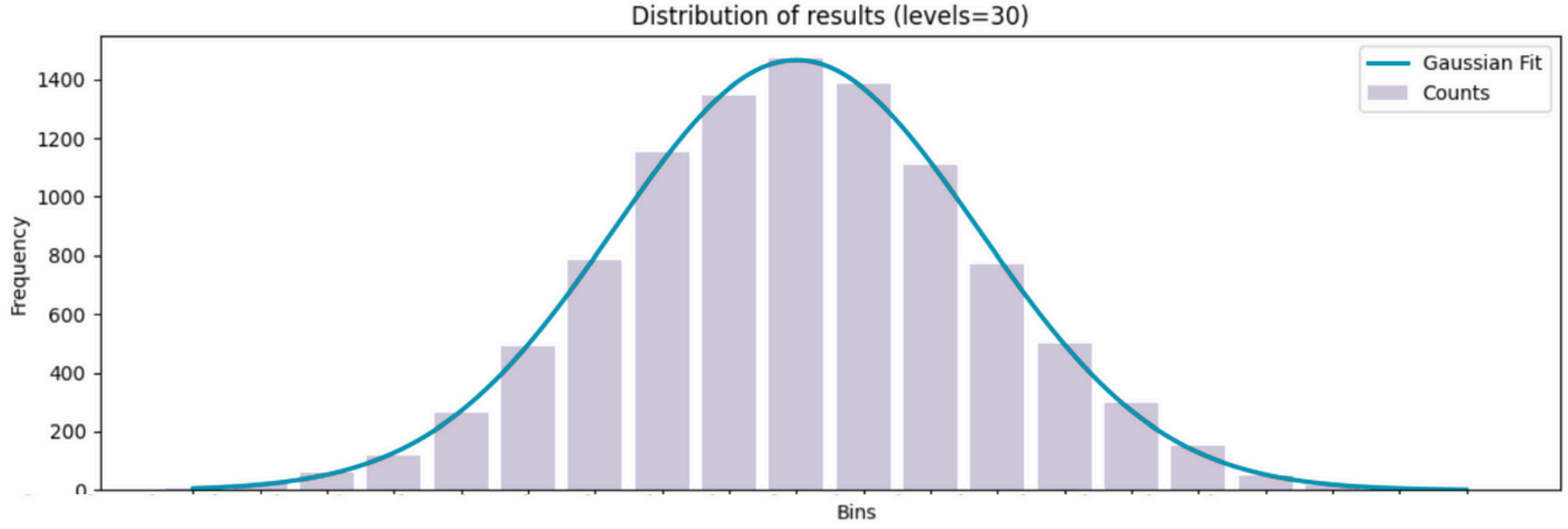
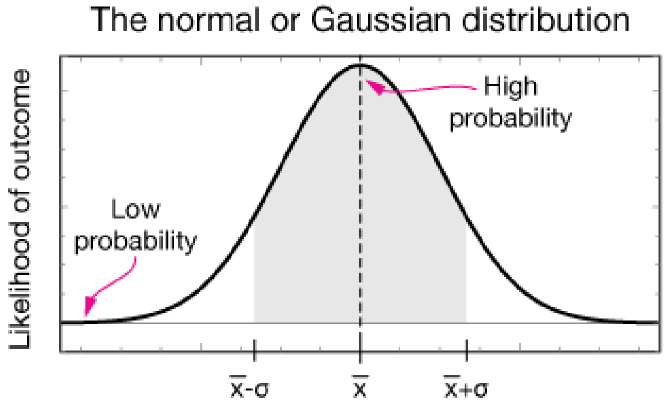


Figure 3: *Gaussian distribution fitted to the histogram of Fig. 2 with values of*

μ= 9.0 = and σ= 2.7.



We obtained a good match with parameters

3. Results and Impact | 3.3 Biased QGB – Exponential Distribution

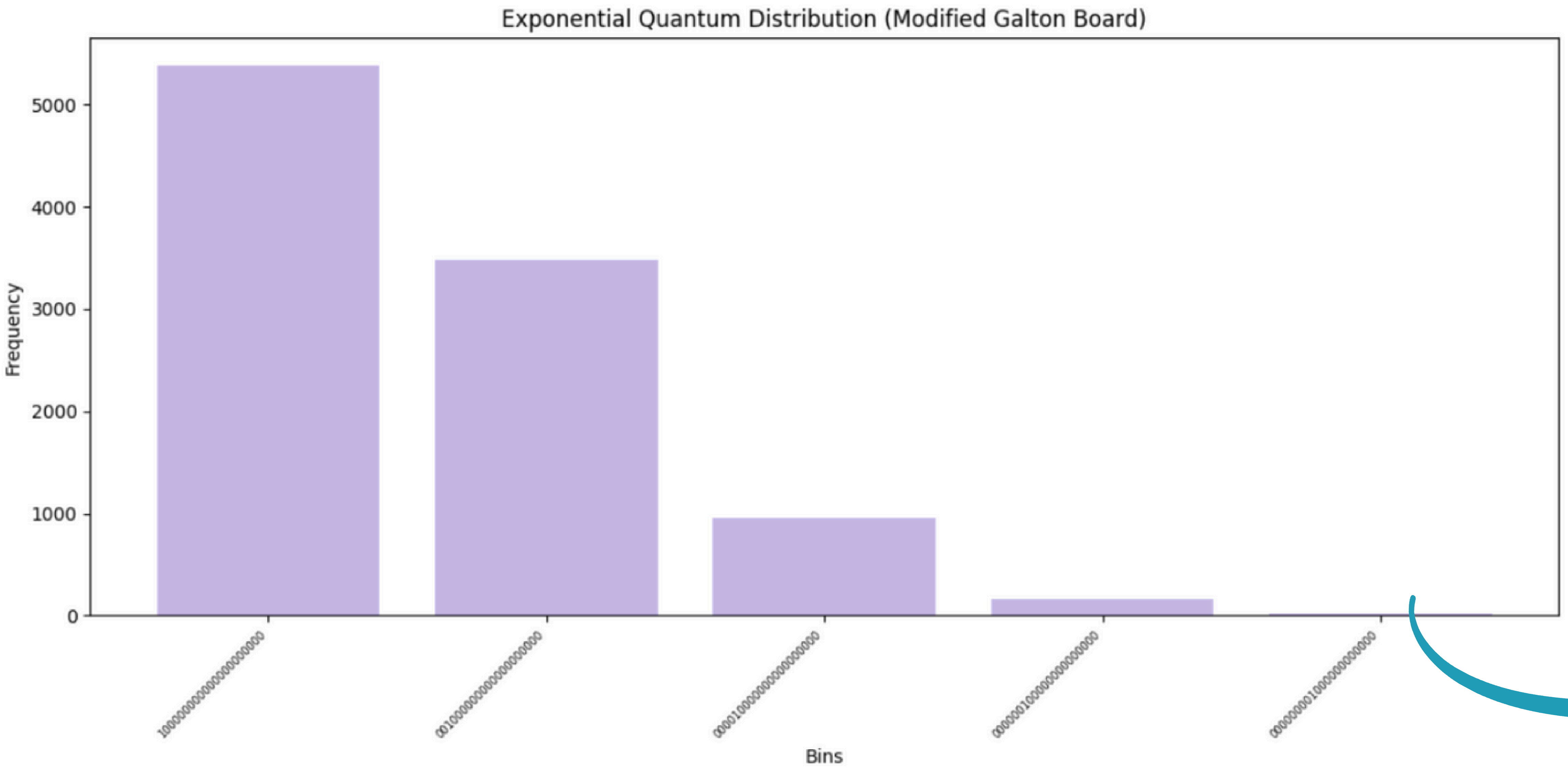


Figure 4: *Output results from the simulation of the 10 levels of exponential quantum distribution, with 10,000 shots.*

The QGB was modified to approximate an exponential probability distribution instead of the typical Gaussian profile.

- The bias was introduced by replacing the Hadamard "coin" with a level-dependent RY rotation

$$\theta_k = \theta_0 e^{-\alpha k}$$

The histogram in the figure was obtained using n= 10 levels and a parameter α= 0.1.

Output distribution shows strong asymmetry and rapid decay from the most probable bin

3. Results and Impact | 3.4 Alternative Quantum Walk – Hadamard

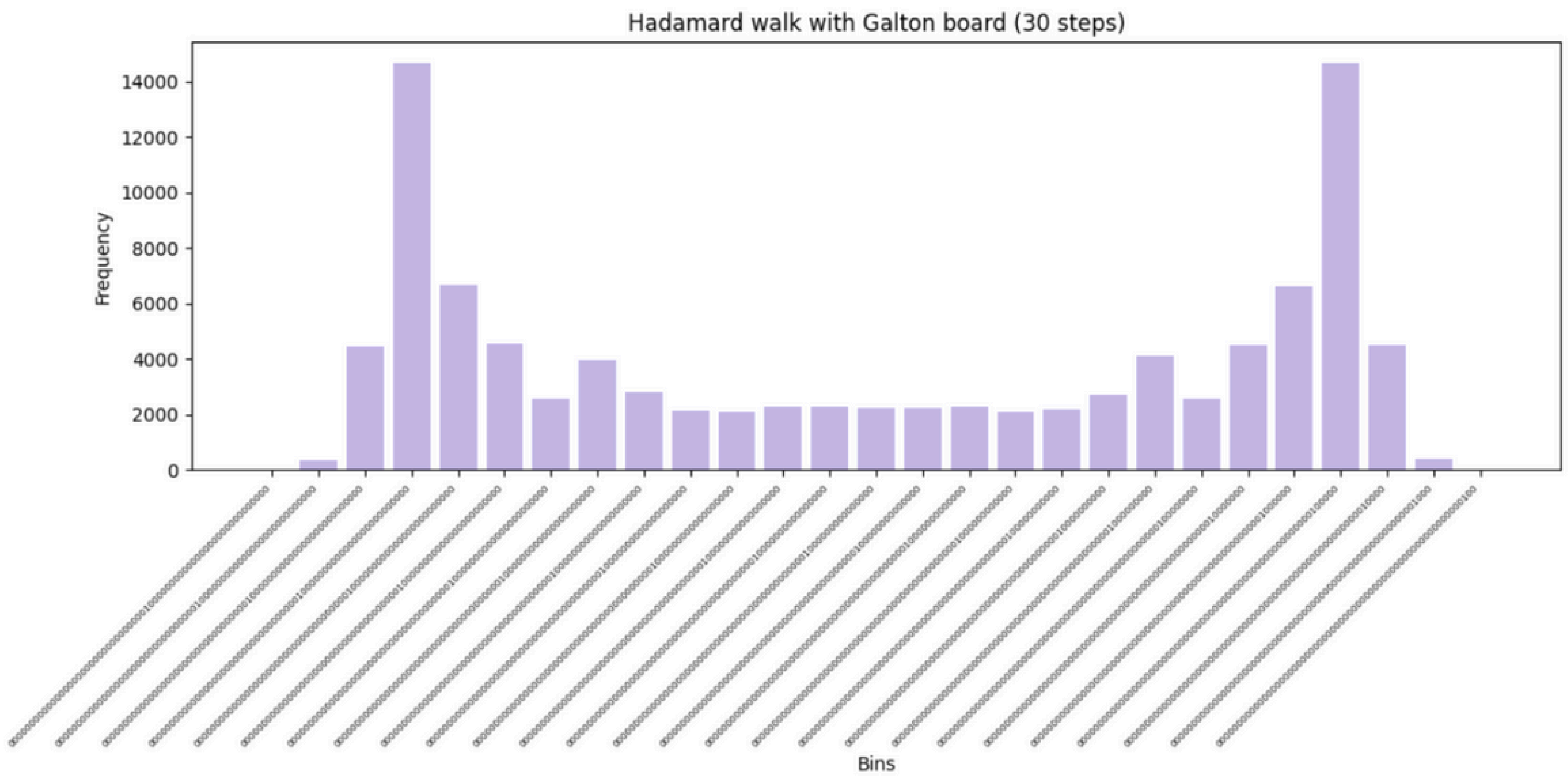


Figure 5: *Output from the Hadamard quantum walk simulation after 30 levels with 100,000 shots.*

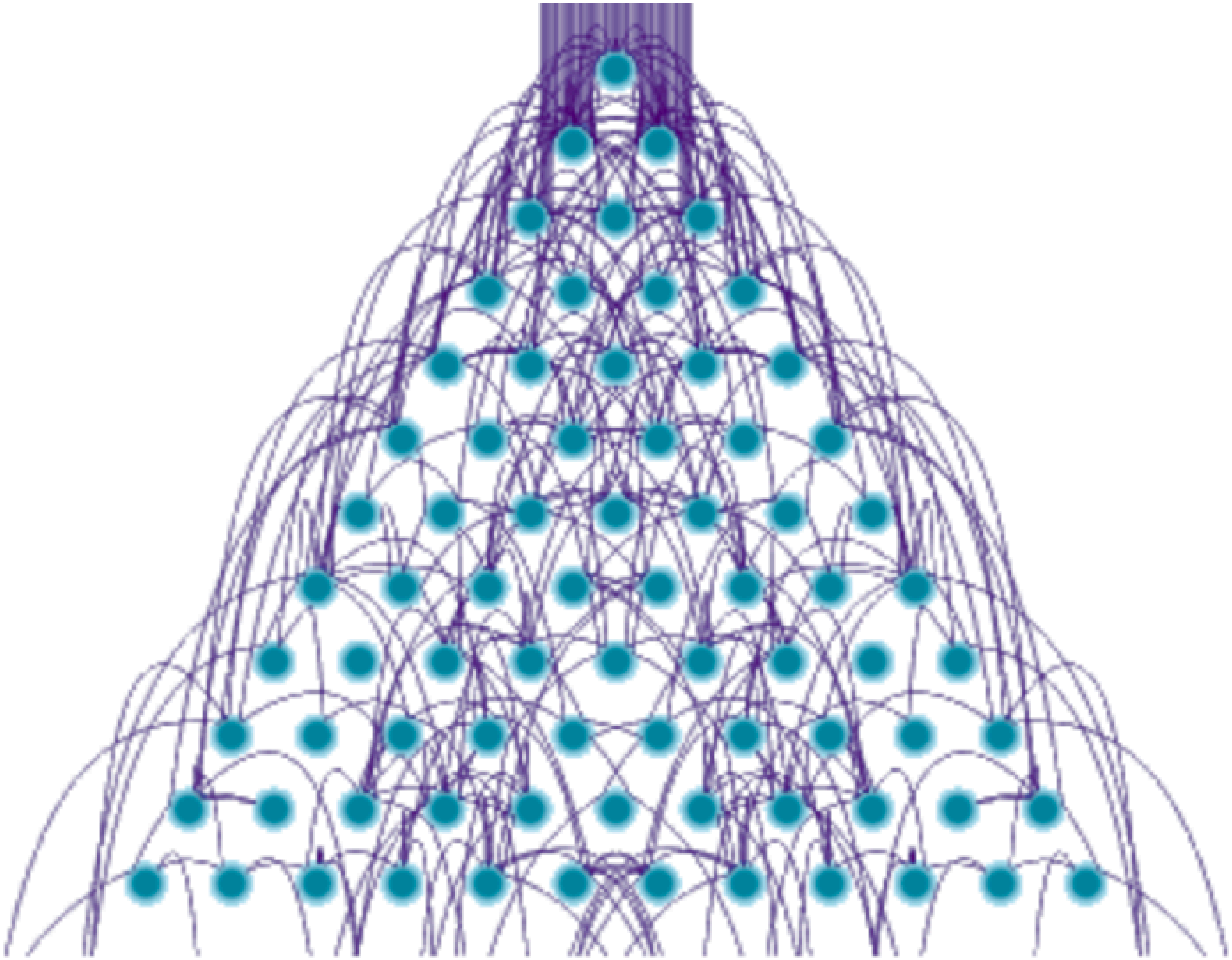
In this variation, the QGB was adapted to implement a discrete-time quantum walk with Hadamard coinoperators applied at each step.

- The Hadamard gate creates equal superpositions, allowing the "quantum ball" to explore all paths simultaneously.
- Interference effects characteristic of quantum walks emerge, producing a bimodal distribution with peaks at the edges instead of the Gaussian shape seen in the unbiased QGB.

The output shows pronounced probability amplitudes at the outermost bins, a hallmark of ballistic spread in quantum walks.

3.5 Impact and Relevance

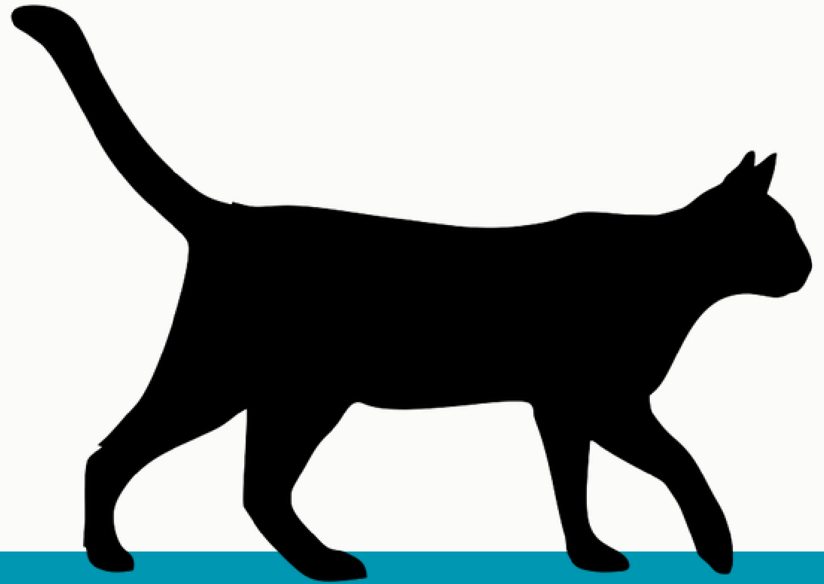
The developed QGB framework demonstrates a scalable design with qubit reuse, enabling the generation of Gaussian, exponential, and Hadamard-walk distributions.
These results validate the flexibility of the architecture for simulating different probability distributions in quantum systems. The implementation in Qiskit, optimized with AerSimulator, provides a ready-to-deploy solution for real quantum hardware, supporting research in quantum sampling and algorithm benchmarking.



4. Future scope

We plan to:

- Extend the QGB to a higher number of levels and qubits.
- Test the design on real quantum hardware, including noise effects.
- Optimize qubit routing to reduce depth and execution time.
- Explore alternative quantum walk variations.
- Investigate applications in sampling for machine learning and physics simulations.
- Consider hybrid quantum–classical approaches for scalability.



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THANKS!

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