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Validation tests of Gaussian boson samplers with photon-number resolving detectors

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The development of linear optical quantum computers (QCs) has accelerated in recent years, in part, due to experimental implementations of large-scale Gaussian boson sampling (GBS) devices. These QCs send squeezed state photons into a linear photonic network and output a series of photon count patterns. This seemingly simple task is $\#P$ -hard because, for implementations utilizing photon-number resolution (PNR), output probabilities correspond to the matrix Hafnian, which cannot be computed in less than exponential time for networks with more than 50-modes.

This raises the question, how does one validate the outputs of such devices to determine whether they are producing the correct results? To answer this, we simulate the binned photon counting probabilities of GBS using phase-space representations.

For networks with photon loss, we show that the positive P-representation is accurate and efficient by simulating the GBS experiments of Madsen et al [1], which claimed quantum advantage on a 216-mode network. Utilizing statistical tests such as χ^2 and Z -scores, we show that these experiments do not produce the correct output distribution. Instead, their distribution more accurately replicates a distribution with additional decoherence and measurement errors, although discrepancies remain.

In the lossless and ultra-low loss regimes, the positive P-representation suffers from large sampling errors and slow convergence. To validate GBS in these regimes, we introduce a new type of phase-space representation: the matrix P-representation. This representation unifies group theoretic and phase-space methods by including symmetries and conservation laws in the basis. We show that, by including a phase symmetry generated from a superposition of Schrodinger cat states, one can simulate the binned photon count distribution in these regimes for very large system size.

[1] L. Madsen. “Quantum computational advantage with a programmable photonic processor.” *Nature* 606, 75-81 (2022).

Author: DELLIOS, Alexander (Swinburne University of Technology)

Co-authors: Prof. REID, Margaret (Swinburne University of Technology); Prof. DRUMMOND, Peter (Swinburne University of Technology)

Presenter: DELLIOS, Alexander (Swinburne University of Technology)

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