Phase-space simulations of Gaussian Boson Sampling quantum networks

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Recent large scale implementations of Gaussian Boson Sampling (GBS) quantum computers have led to claims of quantum supremacy by Zhong et al [1, 2]. These implementations use squeezed vacuum state inputs into a photonic network to measure photon coincidence counts using efficient "on-off" detectors. The probability of observing a single output pattern is the #P-hard distribution called the Torontontian. These experiments measure up to 113th-order coincidence counts, which they claim is beyond the realm of classical computation. This leads to an interesting problem; How does one compare theoretical and experimental outputs if one cannot classically compute them?

To answer this, we introduce the idea of a grouped count probability which can be efficiently measured and simulated using phase-space representations of quantum states. Using the positive-P phase-space method, we compare data sets from both GBS experiments to theoretical grouped probabilities, which have the same moments as experimental outputs. Statistical tests such as χ^2 tests are used to show the degree of agreement between theory and experiment. For example, we obtain a χ^2 value of $\approx 8.5 \pm 1$ for the data set with 113 recorded coincidence counts only after one includes additional decoherence which is required to obtain agreement between outputs. We extend these results to include comparisons of grouped probabilities with mutlidimensional outputs, which allow one to obtain a more fine grain comparison. Comparisons of click correlations up to 4th-order are also included due to their importance in generating classical fake data sets. Grouped probabilities allow one to generate all possible click correlations in bosonic networks in a relatively short computation time.

Our results show agreement with experimental probabilities for one-dimensional outputs once additional decoherence is added, although large discrepancies remain. Increasing the grouped probability dimensionality and the order of click correlations shows increased differences between experimental outcomes and theoretical predictions.

[1] H.-S. Zhong, H. Wang, Y.-H. Deng, M.-C. Chen, L.-C. Peng, Y.-H. Luo, J. Qin, D. Wu, X. Ding, Y. Hu et al., Science 370, 1460 (2020).

[2] Zhong, H.S., Deng, Y.H., Qin, J., Wang, H., Chen, M.C., Peng, L.C., Luo, Y.H., Wu, D., Gong, S.Q., Su, H. and Hu, Y., 2021. Physical review letters, 127(18), p.180502.