Simulation of bosonic qubits using tensor networks

Jean-Baptiste Bertrand[1] and Baptiste Royer[1]

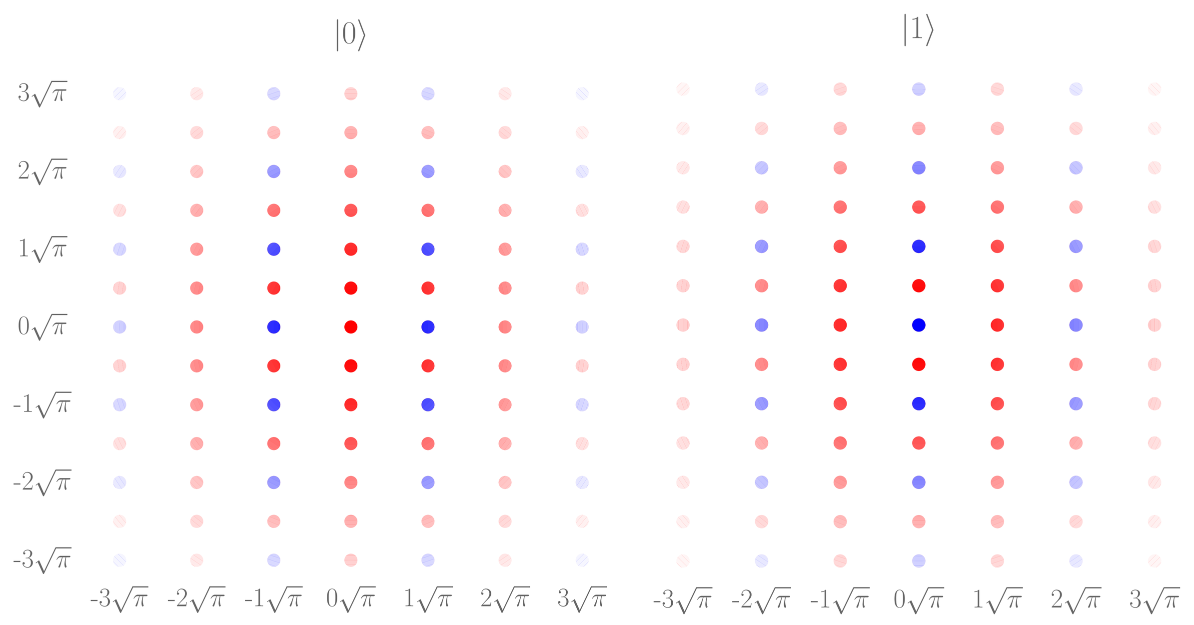
1. Institut quantique, Université de Sherbrooke, Sherbrooke, Qc. J1K 2R1, Canada

Abstract

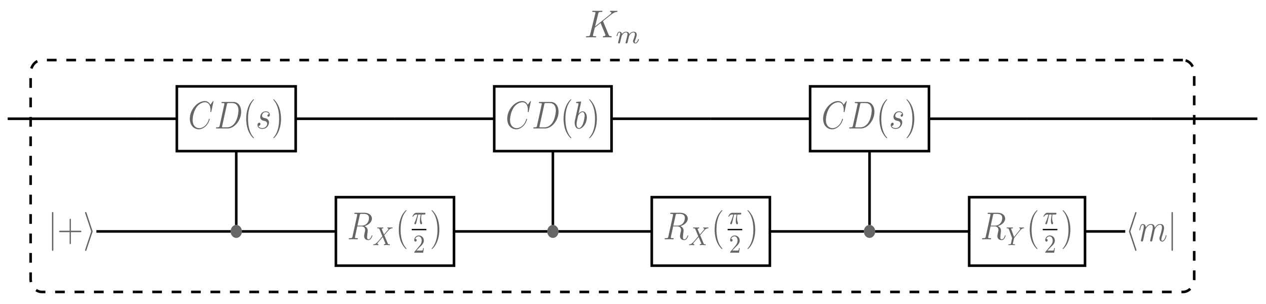
Creating qubits that are resilient to errors is a necessary step in creating quantum computers. A very promising way of accomplishing this is to encode qubits into the large Hilbert space of quantum harmonic oscillators. This idea leads to a whole class of Quantum Error Correcting codes (QEC codes) called bosonic codes. Many popular codes exists but the work here presented mainly focuses on GKP (Gottesman-Kitaev-Preskill) codes [1]. When developing such codes, it is essentiel to be able to know how they perform under different noise models. However, the useful large Hilbert space of harmonic oscillators here becomes a problem as system with even just a few oscillators rapidly become very challenging to simulate. Here, we propose a combination of different methods that would enable fast simulation of *large* bosonic systems. Namely, we discuss the uses of tensors networks, the selection of a simulation basis (the BP+ basis), and the use Monte-Carlo simulationd (MC). We also present a few preliminary simulation results using these techniques.

GKP states

GKP (Gottesman-Kitaev-Preskill) states encode qudits into translationaly invariant states (grid states) in the Fock space of harmonic oscillator. This way of encoding information makes qubits thats are particullarly resilient to information loss.



Stablization



Choosing a basis

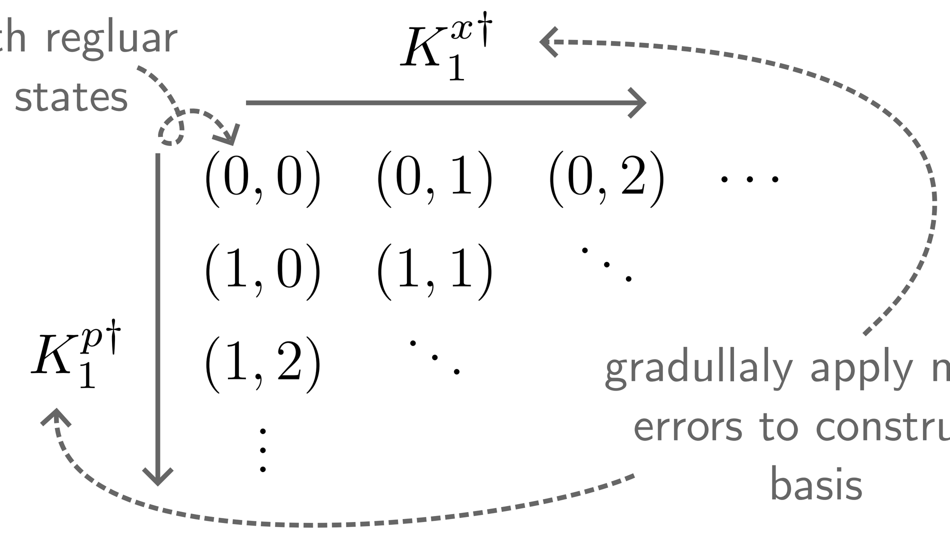
Choosing the right basis for simulation is useful in order to exploit fully some powerful approximation.

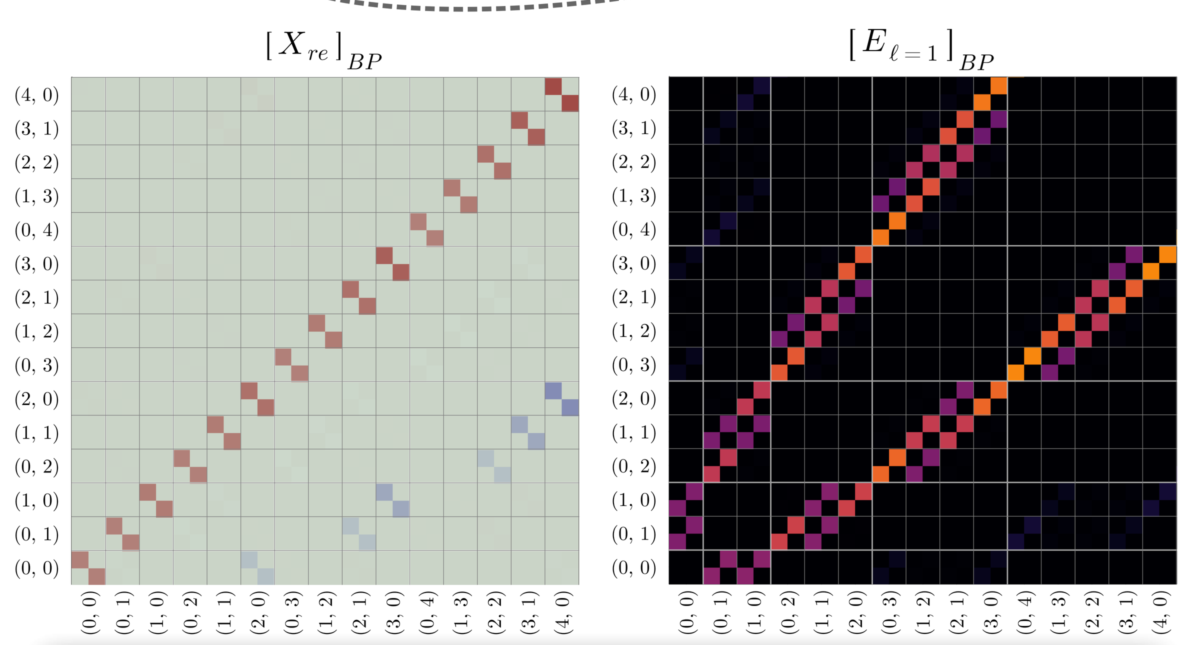
$$\mathcal{H}_{\text{boson}} = \mathcal{H}_l \otimes \mathcal{H}_e$$

Splitting the space into a logical and an error space

sBs basis

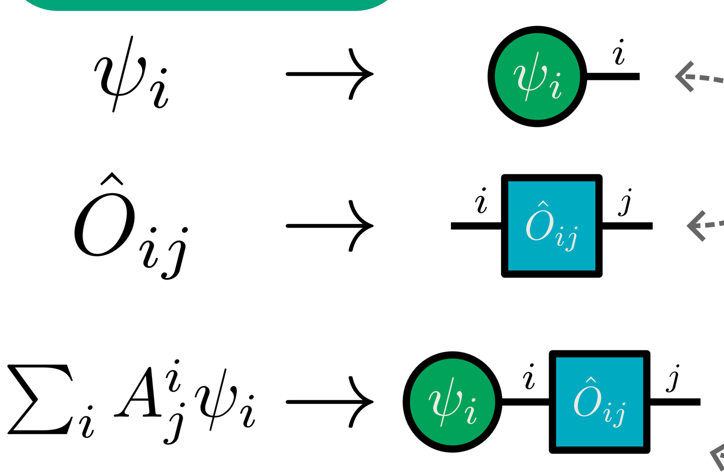
Considering the sBs correction protocol as an operator, it is possible to use this operator to construct a basis [3]. Starting from the pure logical GKP state, you can succesively apply the *inverse* of the sBs operator (Here named K) in order to gradually increase the number of error in your state.



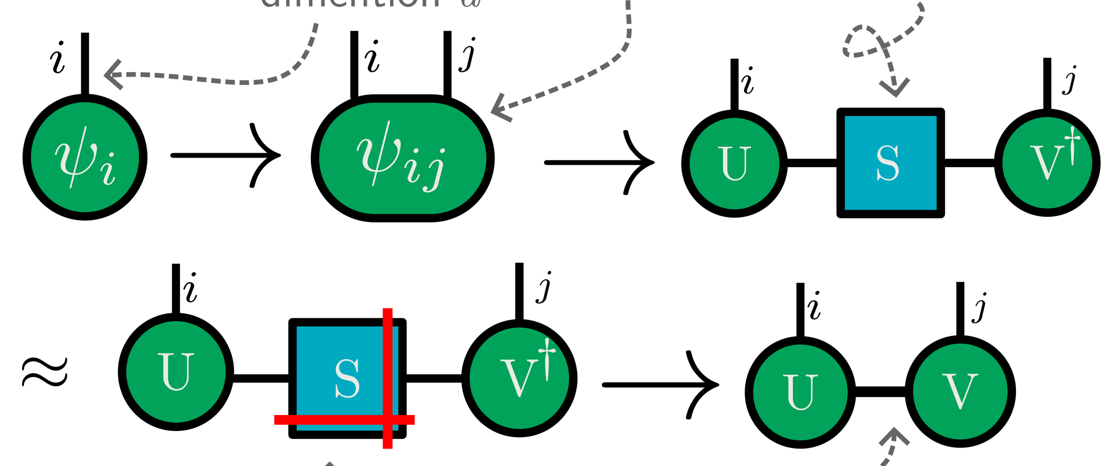


Tensor Networks

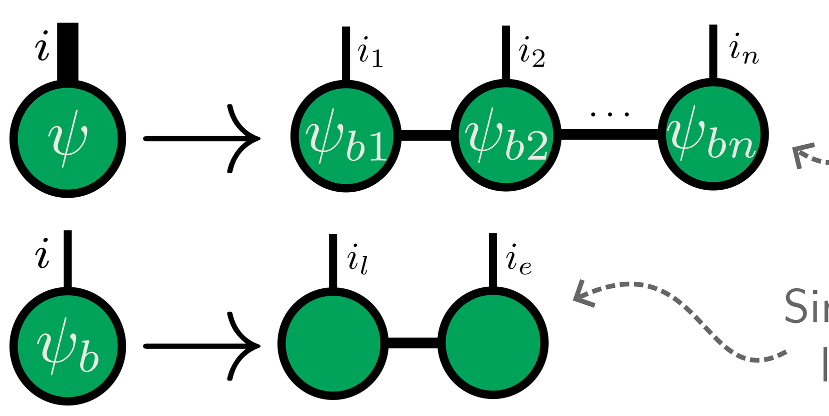
Basics



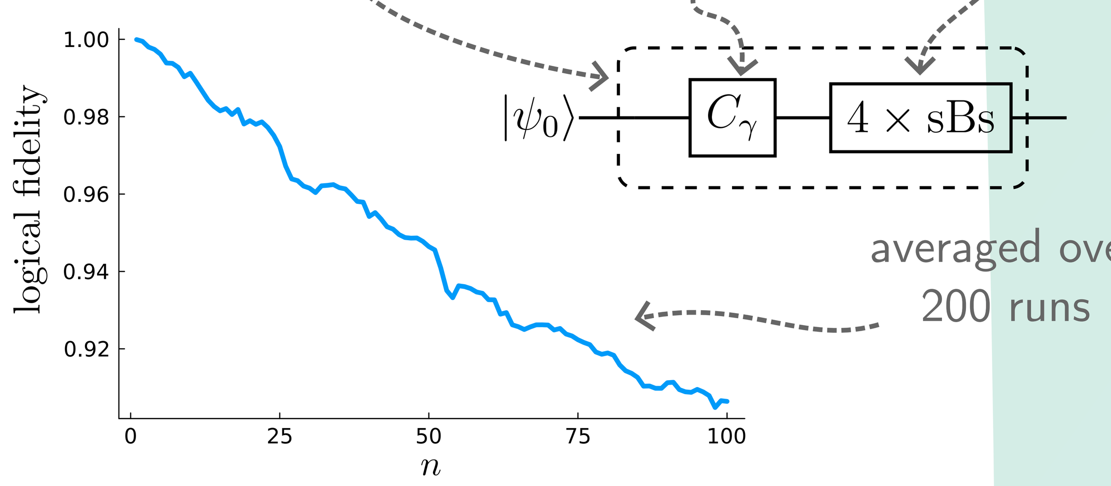
SVD

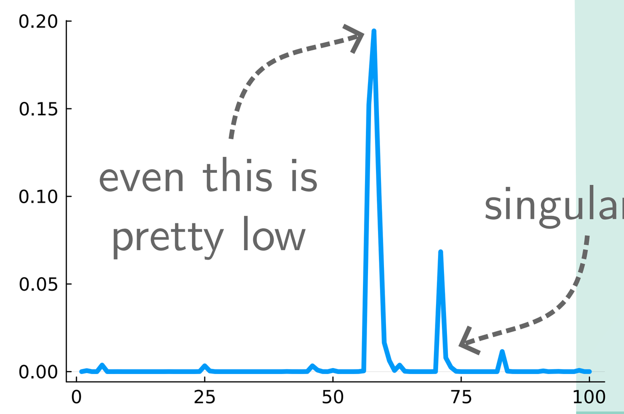


By appying SVD decomposition between on large state vector, you can decompose them into a product of n tensors. Triming the smallest singular values is equivalent to approximating low entenglement between two parts of the system. When running quantum circuit, we expect mostly the logical spaces to be entengled rather than the whole space. We therefore expect that approximating low entenglement between two bosonic qubits will generate good results.



Preliminary results





Next steps

Simulating more complex circuits

- Simulating concatenated codes
- Simuling more complex algorithms

Studying the capacities and limitations of the approch

- Measuring the effect on accuracy of reducing the entenglement between different bosonic modes
- Modeling different noise models

References

[1] Gottesman, D. et al. Phys. Rev. A 64, 012310 (2001)
[2] Royer, B. et al. Phys. Rev. Lett. 125, 260509 (2020)
[3] Hopfmueller, F. et al. (2024)

Acknowledgements

This work was funded by the Canada First Research Excellence Fund, the National Science and Engineering Council and the Fonds de Recherche du Québec - Nature et Technologies. This work was done in collaboration with Nord Quantique.

Université de Sherbrooke
Nord Quantique
NSERC CRSNG
Fonds de recherche Nature et technologies Québec