Preparing Ground States for Quantum Computation of Gauge Theories

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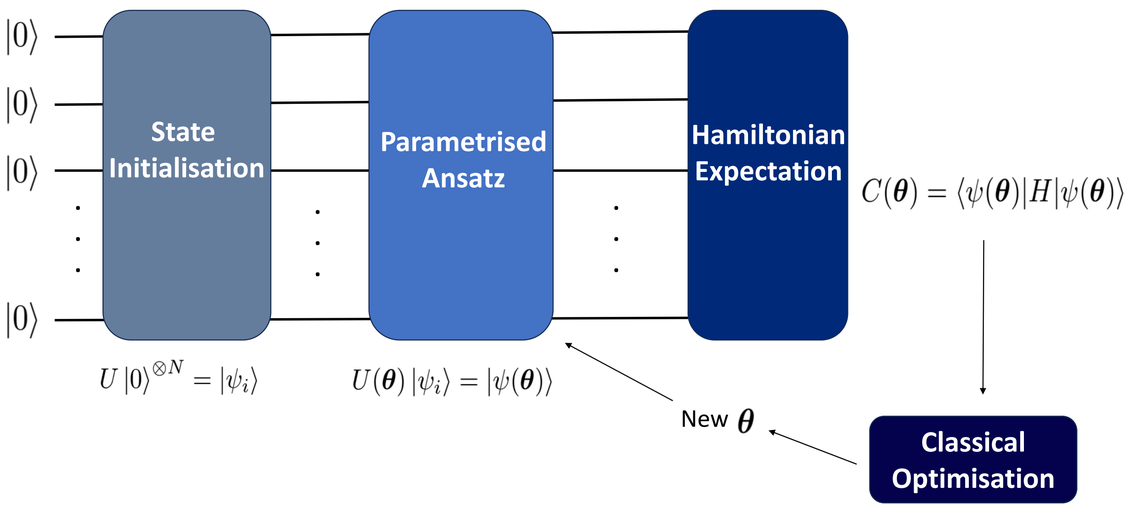
Motivation

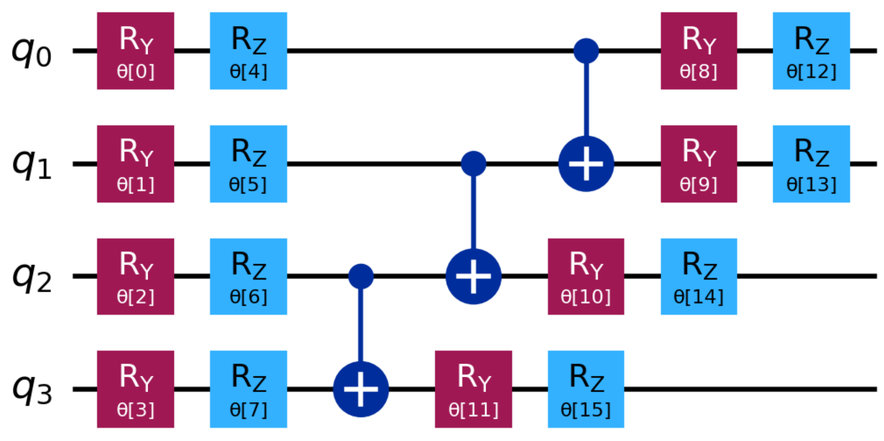
Simulation of adiabatic methods on a quantum computer has been successfully used to prepare ground states of gauge theories [1]. However, this process requires a high number of quantum gates, which is inaccessible in the NISQ era. An alternative approach is to use variational methods to attempt to reduce the gate count.

Variational Quantum Eigensolver (VQE)

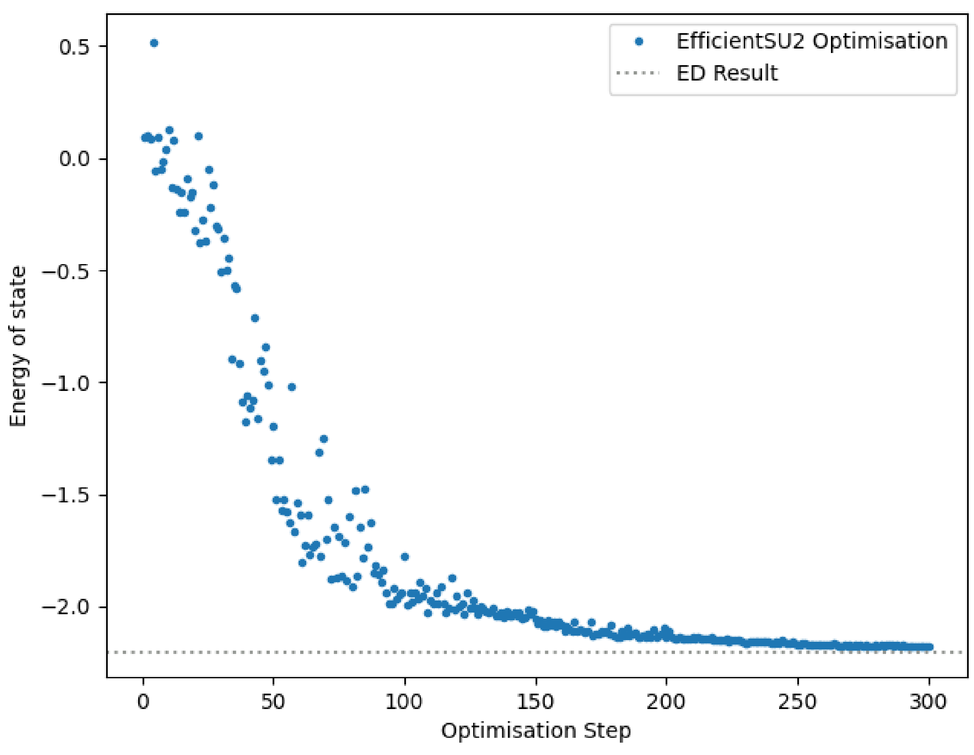
VQEs utilise a combination of quantum and classical computation. The quantum computer prepares a parametrised state with an ansatz circuit and measures its energy. Then the classical computer optimises over the parameters until the ansatz prepares an approximation of the ground state [2].



A standard choice of ansatz is a hardware efficient ansatz, such as IBM's EfficientSU2:



This ansatz can be repeated in layers, but this increases the number of parameters and optimisation becomes harder. An example of optimisation with three layers is shown below, approaching a theoretical result found using exact diagonalisation.

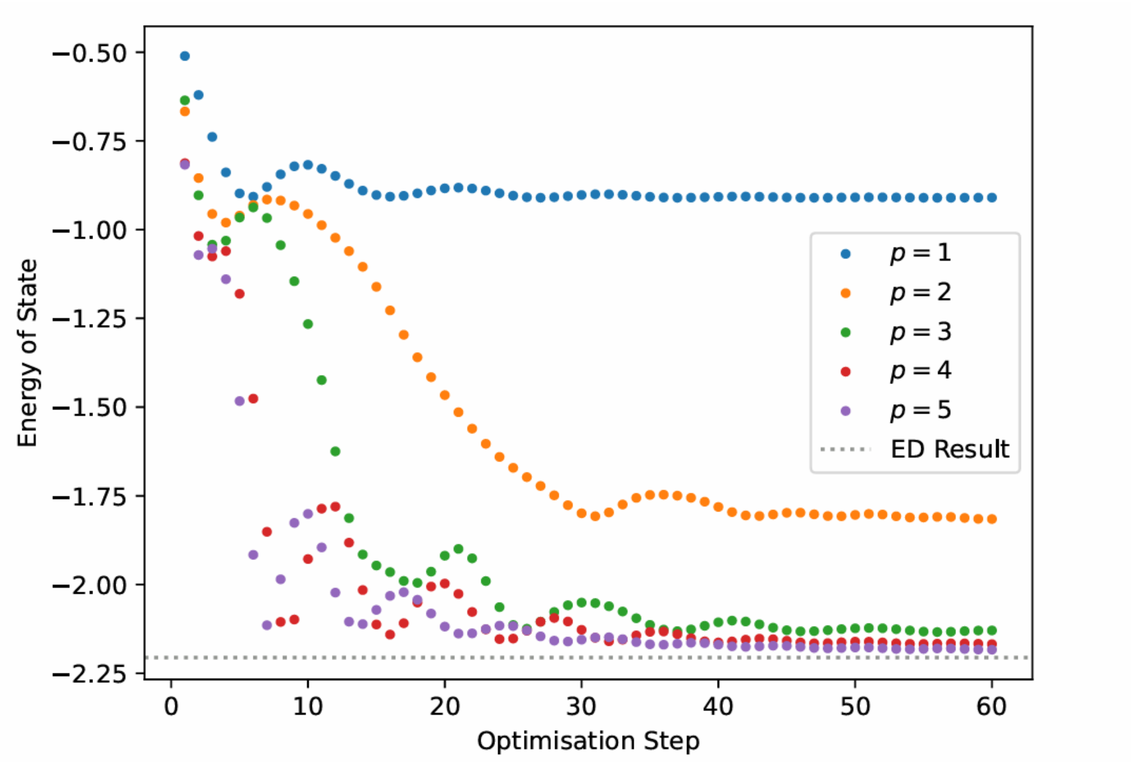


Quantum Adiabatic Approximation Algorithm (QAOA)

An alternative approach to ansatz design is making it problem specific. QAOA is one option for this and uses the original cost Hamiltonian in the functional form of its ansatz [3].

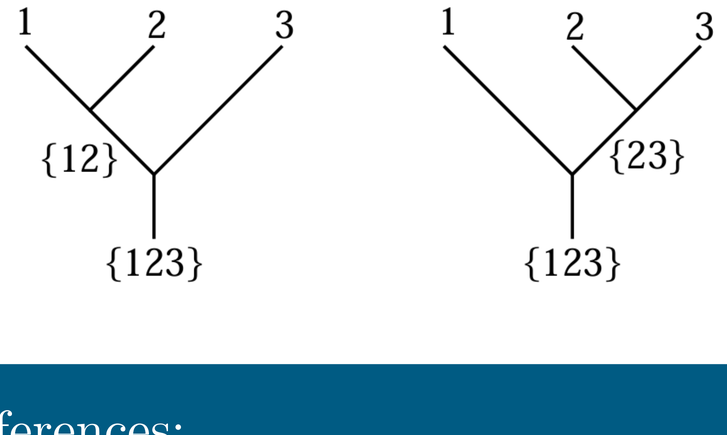
$$|\psi_p(\boldsymbol{\beta},\boldsymbol{\gamma})\rangle = e^{-i\beta_p\hat{H}_M}e^{-i\gamma_p\hat{H}_C}\ \ldots e^{-i\beta_1\hat{H}_M}e^{-i\gamma_1\hat{H}_C}\,|\psi_i\rangle$$

Like before we choose how many layers p to use. We also need a mixer Hamiltonian to prevent getting stuck in a higher eigenstate. Results for the same problem as before are shown. Provided enough layers are used improvement to optimisation can be seen, whilst still being accessible on NISQ devices.



Permutational Quantum Computing

The choice of mixer can affect the performance of QAOA. We expect to see improvement using the Sn-CQA ansatz according to [4], but this utilises a different model of quantum computing called permutational quantum computing [5]. Here, we utilise the simultaneous eigenstates of angular momentum operators of coupled qubits. Algorithms then involve permuting qubits before measurement. Implementation of this is currently work in progress.



References:

[1] Chakraborty et al. (2022) Phys. Rev. D 105, 094503
[2] Puruzzo et al. (2014) Nat Commun 5, 4213
[3] Farhi et al. (2014) arXiv:1411.4028
[4] Zheng et al. (2023) PRX Quantum 4, 020327
[5] Jordan (2009) arXiv:0906.2508

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