Parallelizing quantum algorithms in the NISQ era

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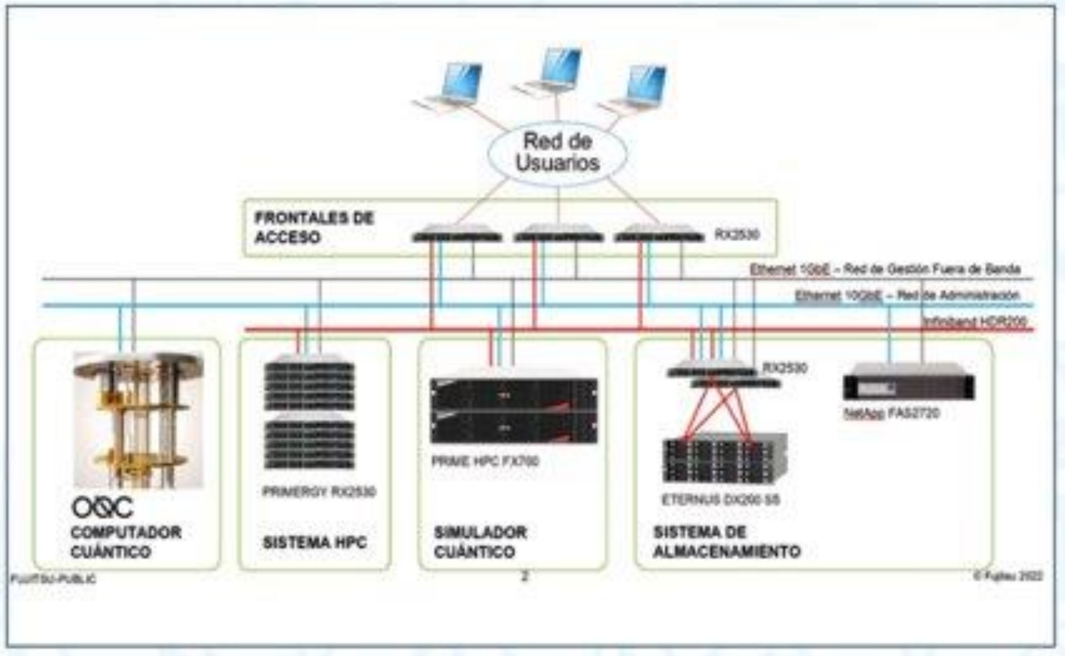
Fundación CESGA

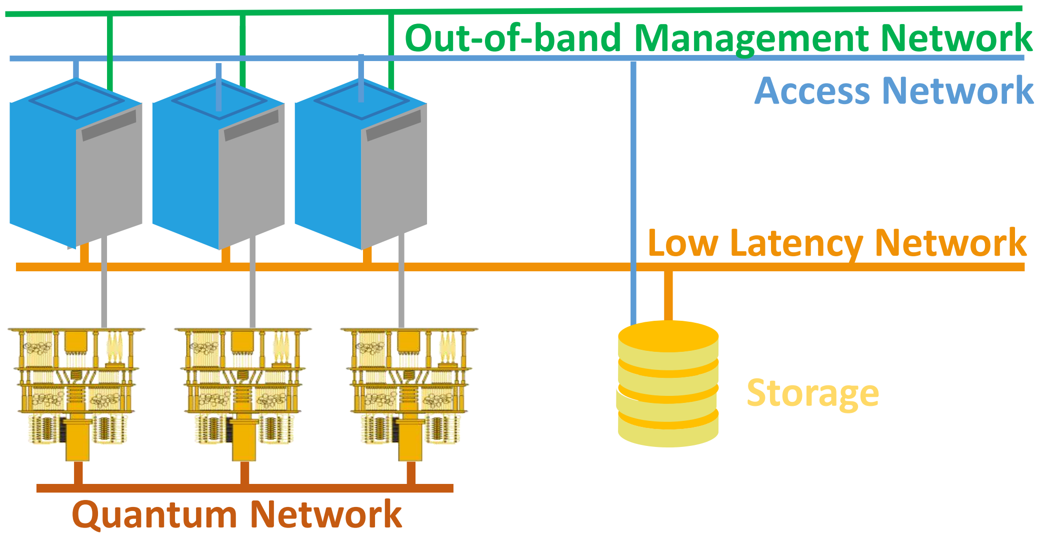
CESGA QUANTUM INFRAESTRUCTURE



1. A 32-qubit quantum computer from OQC
2. An emulator based on mpiQULACS and Fujitsu technology
3. An HPC system for Quantum Computing research
4. Dedicated storage.

Soon available for CESGA users!!

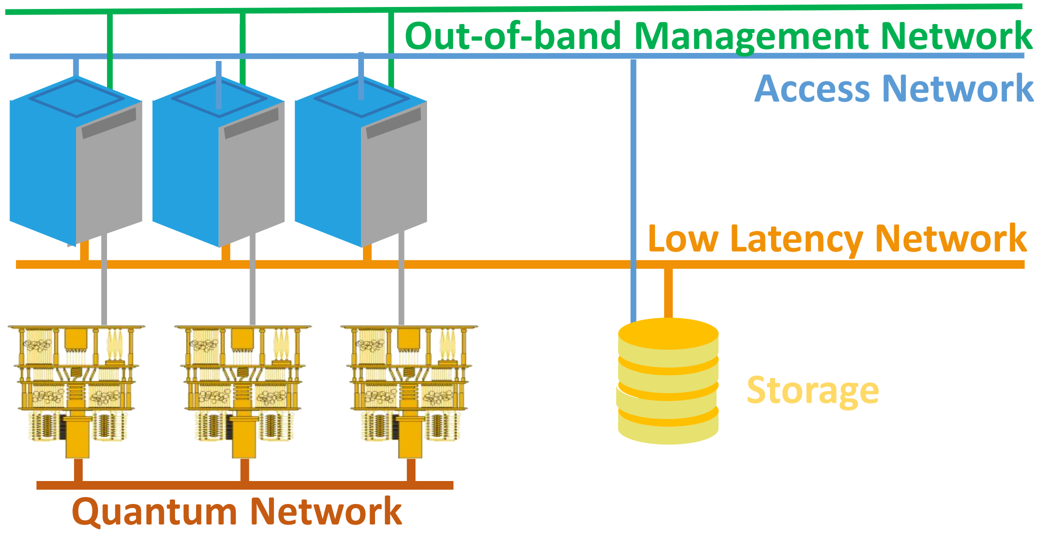
CESGA VISION: PARALLEL QUANTUM COMPUTING



Parallel execution of a quantum algorithm depends on available hardware

No communication → Classical communication → Quantum communication

CESGA VISION: PARALLEL QUANTUM COMPUTING



Parallel execution of a quantum algorithm depends on available hardware

No communication

Classical communication

Quantum communication

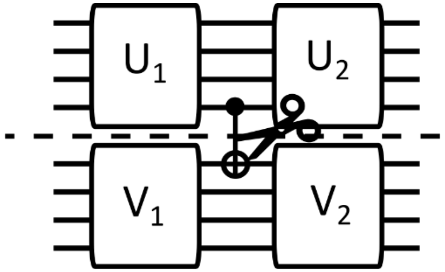
We are here

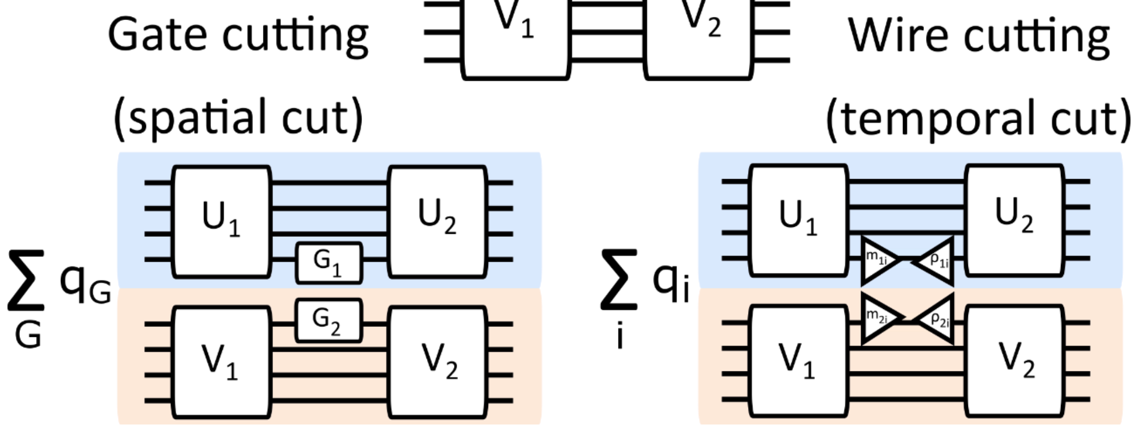
CIRCUIT CUTTING

Two QPUs can execute the same algorithm if the entanglement between them is simulated

Available techniques:

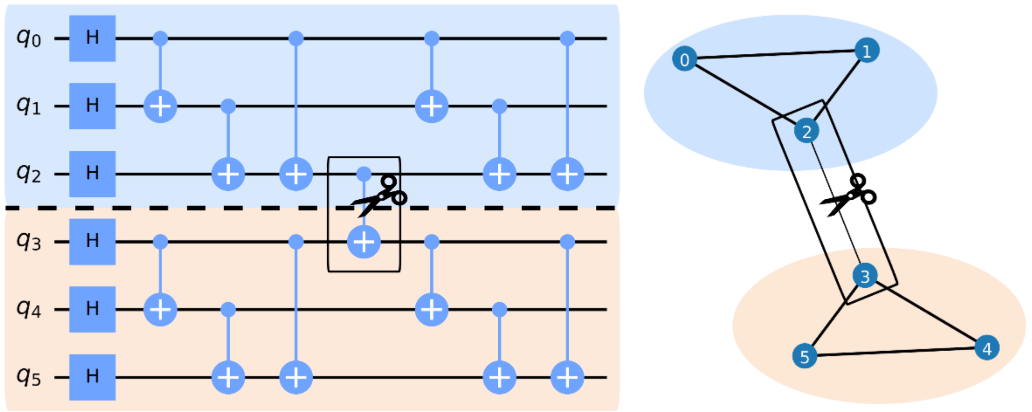
- Wire cutting (CutQC library)
- Gate cutting





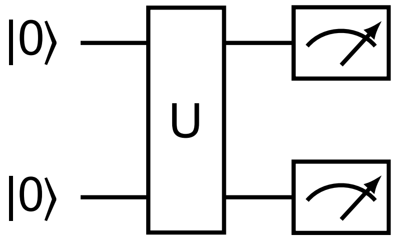
Finding optimal circuit division: minimize N_{cuts}

- Equivalent to solving a graph problem: Minimum-k cut



Cutting a single gate

Gate cutting relies on quasi-probability simulation of single gates

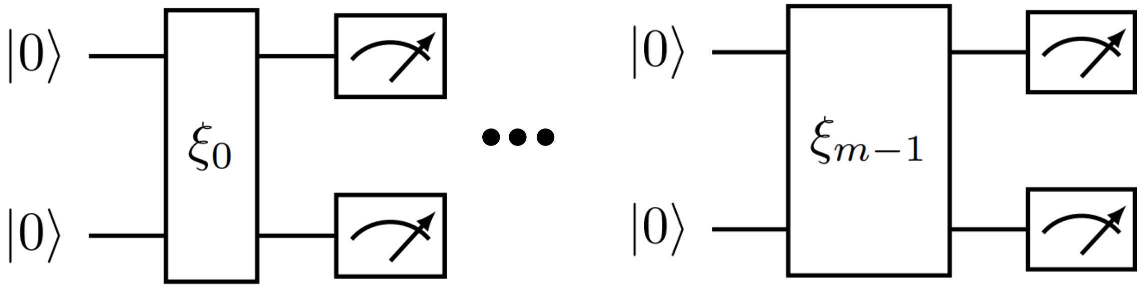


$\xi_U \rightarrow Represented\ by\ the\ superoperator\ C_U$

Quasiprobabilistic decomposition

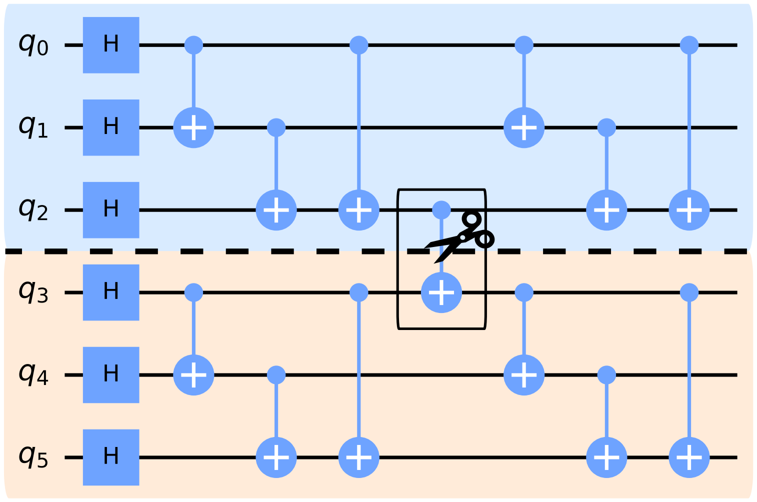
$$\{q_i \in \mathbb{R}, C_i \in CPT\ maps^*\} \rightarrow\ C_U = \sum_{i=0}^{m-1} q_i C_i^*$$

$*\ such\ that\ C_i\ represent\ local\ circuits$

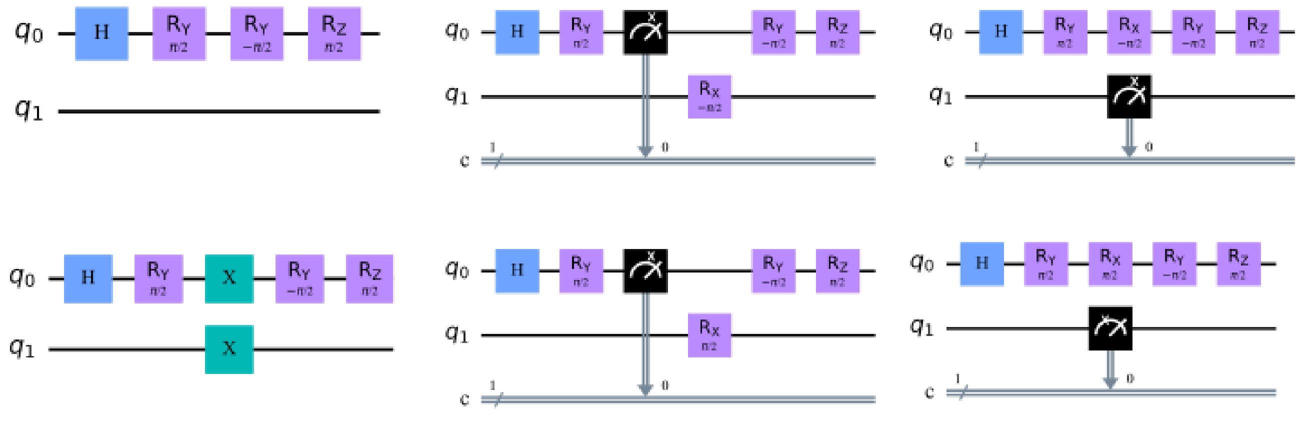


CNOT gate simulation

$$C_{CNOT} = \sum_{i=0}^{m-1} q_i C_i = \frac{1}{2}C(I \otimes I) + \frac{1}{2}C(\sigma_x \otimes \sigma_x) \pm \frac{1}{2}C\left(R_\alpha\left(\pm\frac{\pi}{2}\right) \otimes (\Pi_x^+ - \Pi_x^-)\right) \pm \frac{1}{2}C\left((\Pi_x^+ - \Pi_x^-) \otimes R_x\left(\pm\frac{\pi}{2}\right)\right)$$



Virtual CNOT gate



Cost of quasiporbalistic simulation associated with the negative terms in the decomposition

l_0 norm of the decomposition
$\kappa = \sum |q_i|$

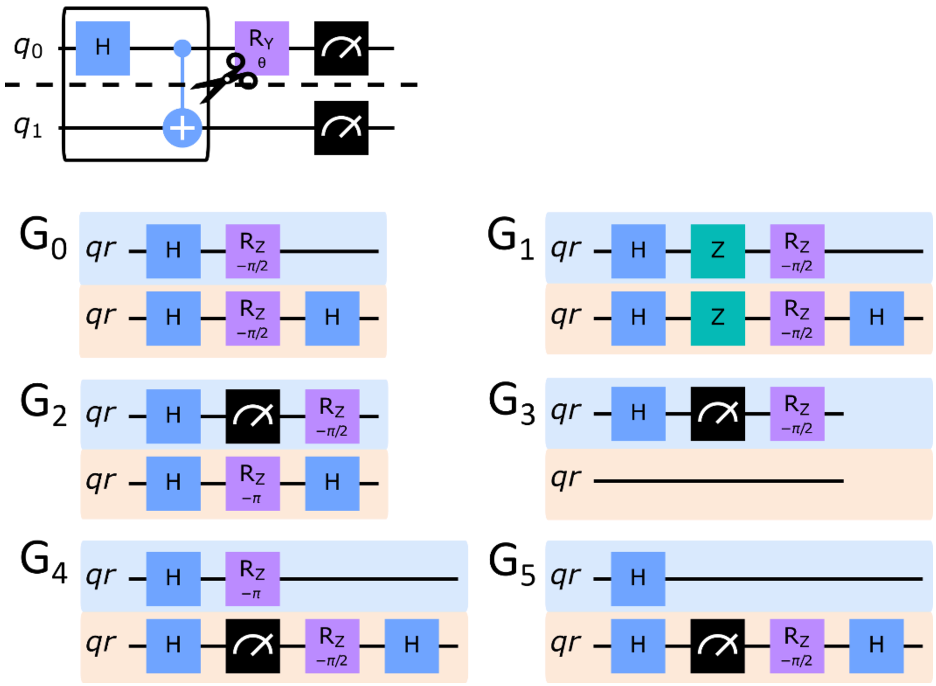
$\kappa_{CNOT} = 3$

Example: Bell test simulation

The Bell test serves as a toy model to test gate cutting.

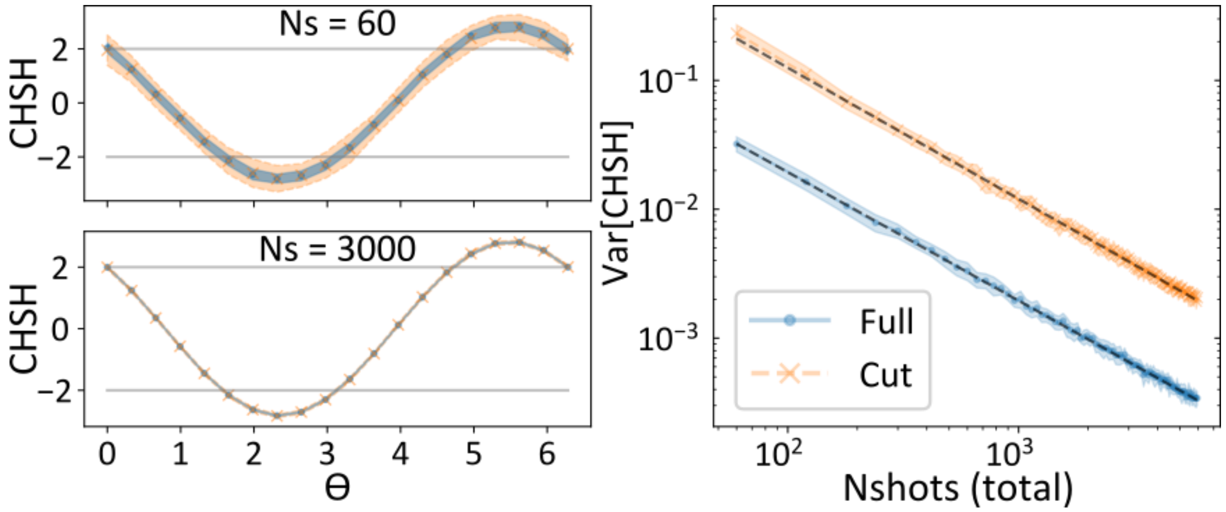
Steps:

1. Execute separately the subcircuits.
2. Combine the weighted result of the subcircuits.
3. Reproduce the Bell test experiment



Example: Bell test simulation

Results



Cost of gate cutting

- Quasi-probability simulation increases the variance of the variance with respect to the original circuit.
- we need more shots/preparations to recover a result with the same precision: **Sampling overhead.**
- The sampling overhead is **exponential** with $\mathbf{N_{cut}}$. Only viable for sparse, low depth circuits (such as VQAs).

Variational quantum algorithms (VQAs)

- VQAs are NISQ friendly (low depth, low width)

- They are hybrid algorithms.

Parametrized quantum circuit
+
Classical optimizer

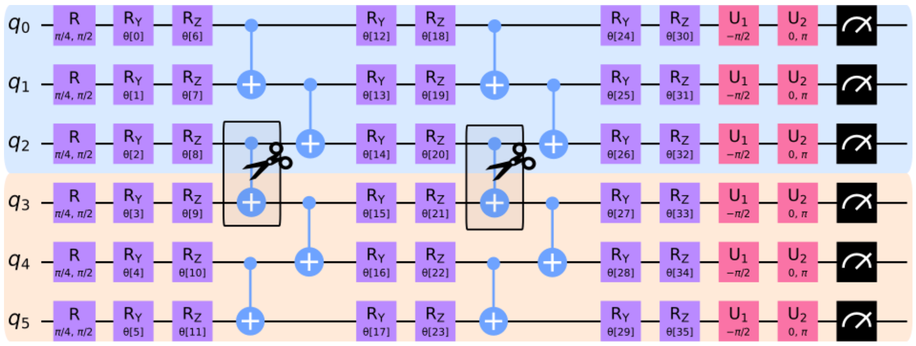
- Two main categories
  - Variational quantum eigensolver (VQE).
    Objective: find the ground state of a physical system (atom, molecule).
  - Quantum approximate optimization algorithm (QAOA)
    Objective: Solve combinatorial optimization problems.

Execution of a VQE algorithm with circuit cutting

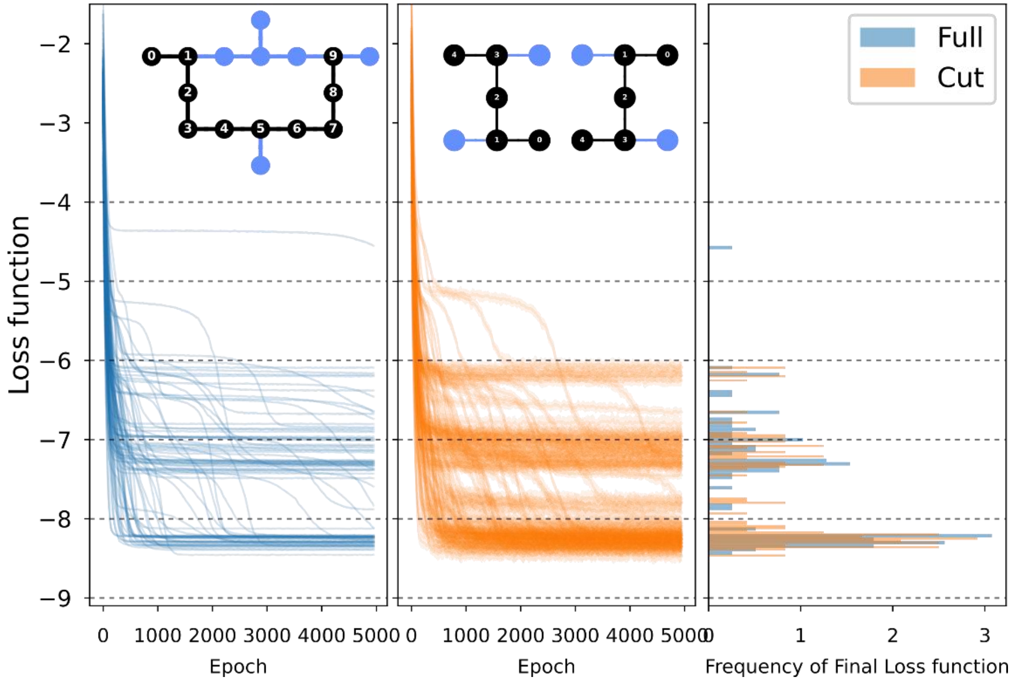
Objective: Find the ground state energy of **1D-Ising model** without external magnetic field using the **Variational Quantum Eigensolver (VQE)** algorithm on two QPUs.

- 10-qubit 1D-Ising model using either a 16-qubit QPU (Full), or a single 7-qubit one (Cut).

Circuit used



Result



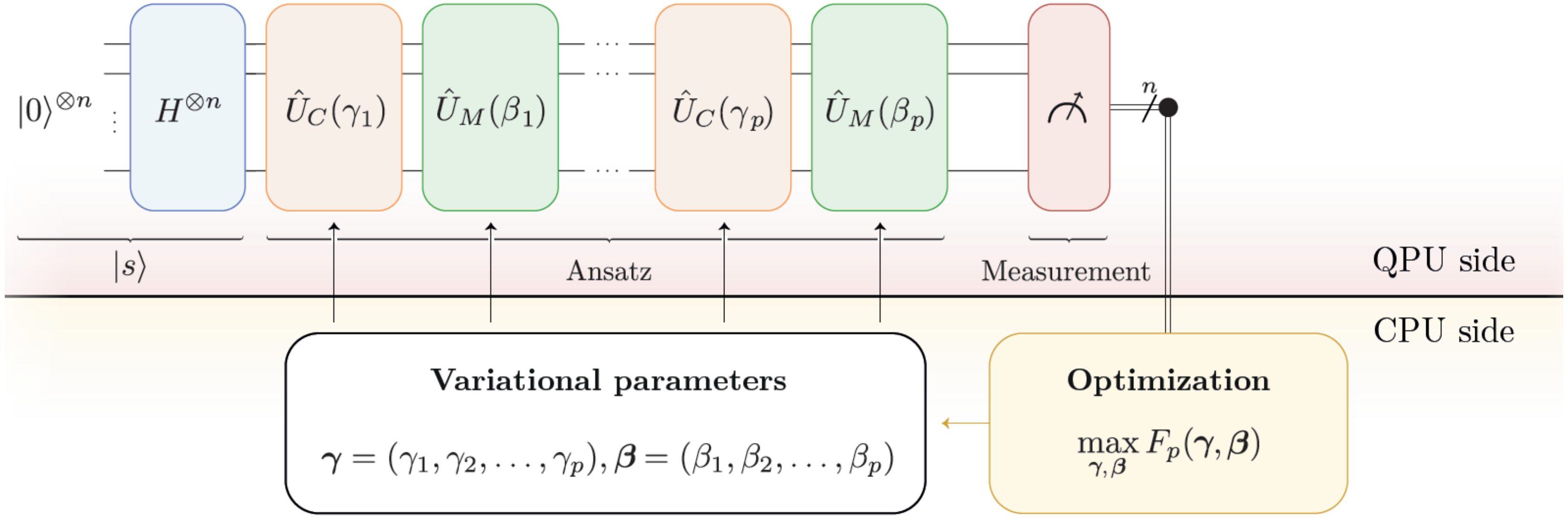
QAOA

Combinatorial optimization problems → Mapped to an Ising-like problem (e.g. max-cut, traveling salesman, jobshop scheduling)

- Quantum annealers (D.WAVE)
- Gate based computer approach:

Discretisation of the evolution via troterization of the hamiltonian QAOA

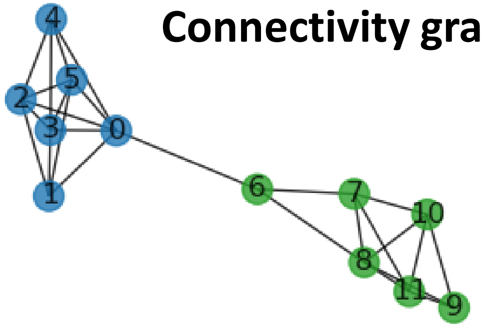
QAOA diagram



Execution of QAOA with circuit cutting

We execute a QAOA algorithm for solving the max cut problem using two QPUs.

Connectivity graph



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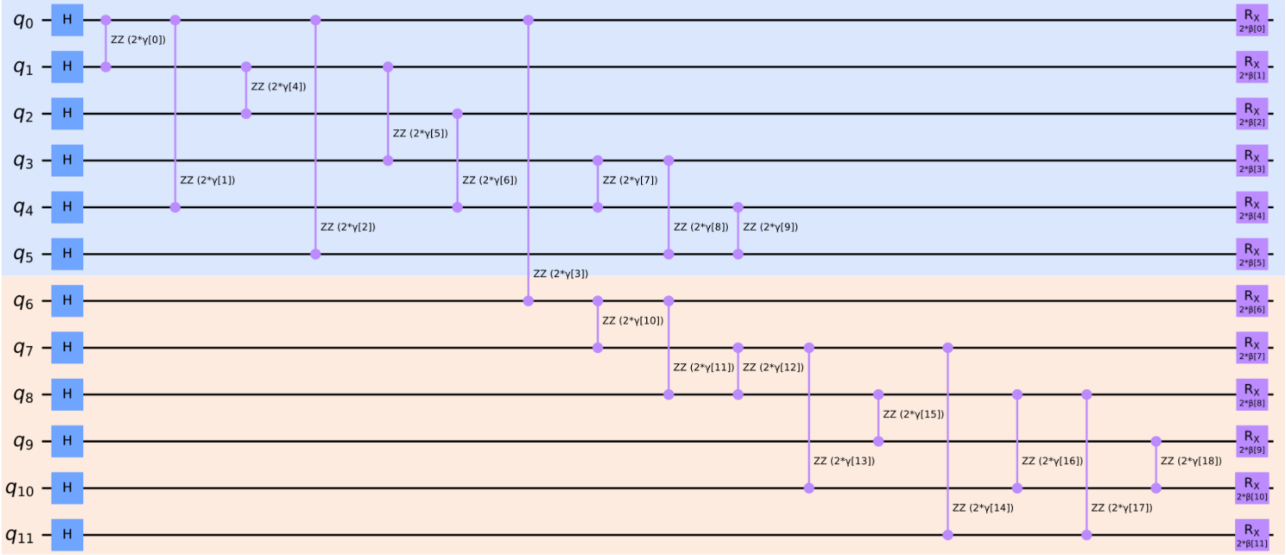
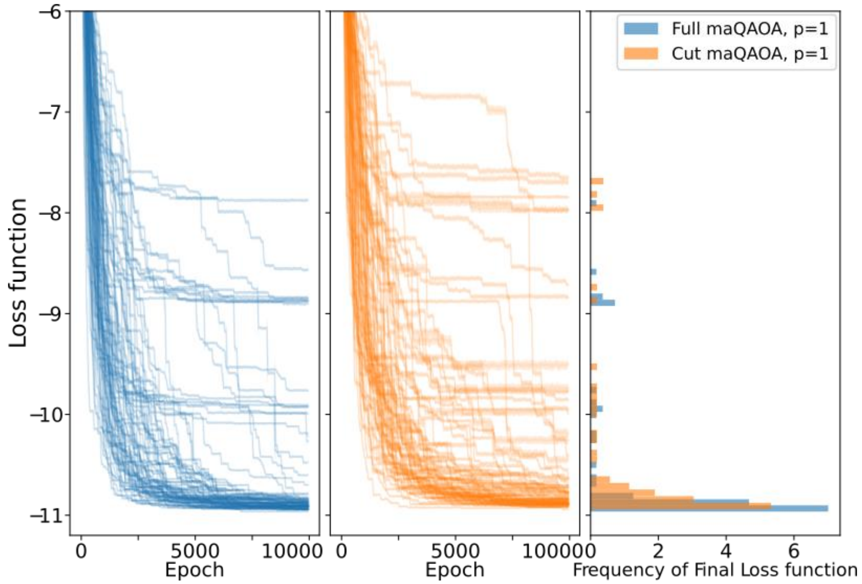


Results



Future work

- Novel circuit cutting schemes, not based on cutting wires or gates.

- Consider the case of more tan two QPUs.

- Explore the scenatios with classical comunication and quantum communication between QPUs (districuted quantum computing)

Gracias

Funding:

AXENCIA GALEGA DE INNOVACIÓN

UNIÓN EUROPEA

Xacobeo 21·22

CESGA GALICIA SUPERCOMPUTING CENTER

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PROGRAMA OPERATIVO FEDER 2014-2020

Una manera de hacer Europa