Introduzione alle macchine PASQAL

Incontri introduttivi al Quantum Computing

Mengoni Riccardo, PhD

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CINECA QUANTUM COMPUTING LAB

Content

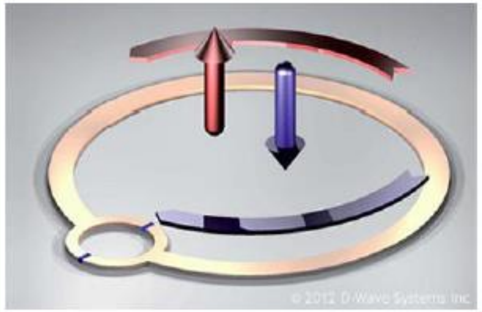
- Intro and Recap
- Pasqal Quantum Hardware: QC with Neutral Atoms
- Pulser: Control Software for Pasqal QC
- Application: QAOA & MIS problem

Intro and Recap

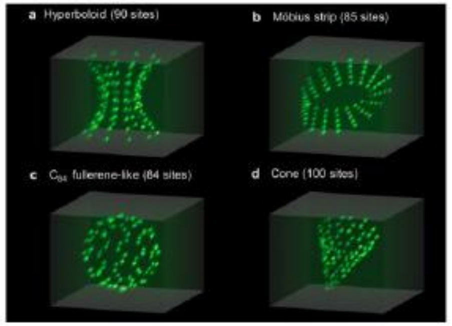
Hardware state of the art – qubit physical realization

PASQAL
|QuEra⟩ Computing Inc.

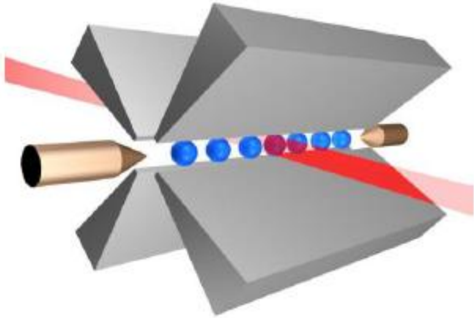
IBM Q
rigetti
D-Wave The Quantum Computing Company™
Google AI Quantum



Superconducting



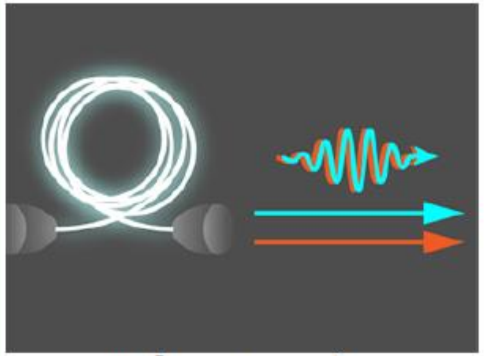
Neutral Atoms



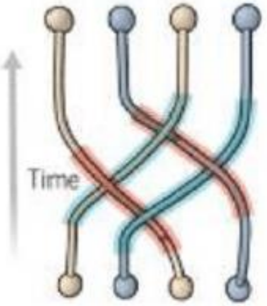
Trapped-Ions

IONQ
QUANTINUUM

XANADU



Photonic



Topological

Diamond Center

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Microsoft

Hardware state of the art – qubit physical realization

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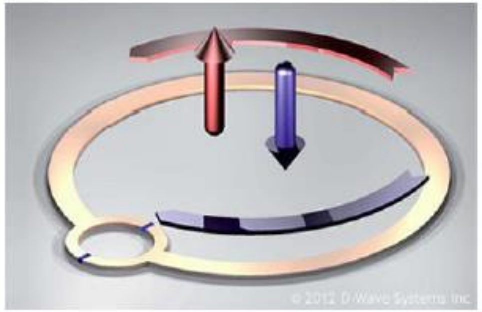
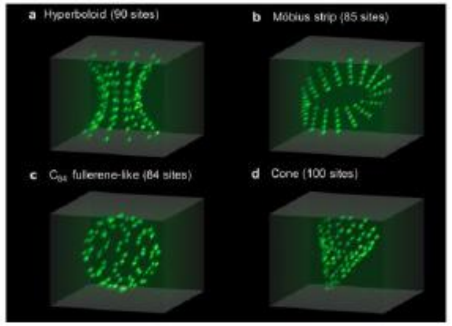
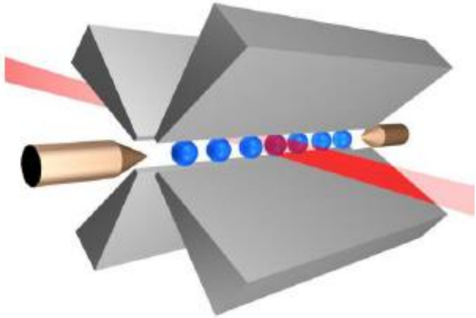


Superconducting

PASQAL



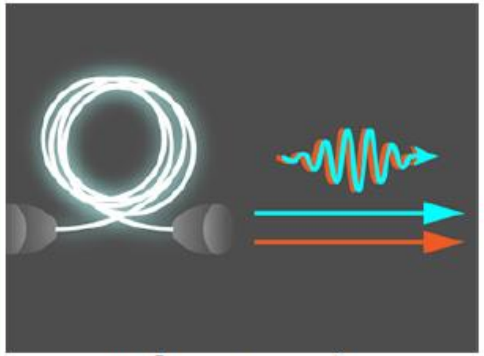
Neutral Atoms



Trapped-Ions

IONQ
QUANTINUUM

XANADU



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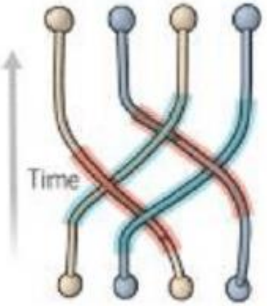

Topological

Microsoft

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EuroHPC - HPCQS

- The **project** will last 4 years, during which it will be created the **conditions** to **integrate quantum simulators with the European HPC network**.

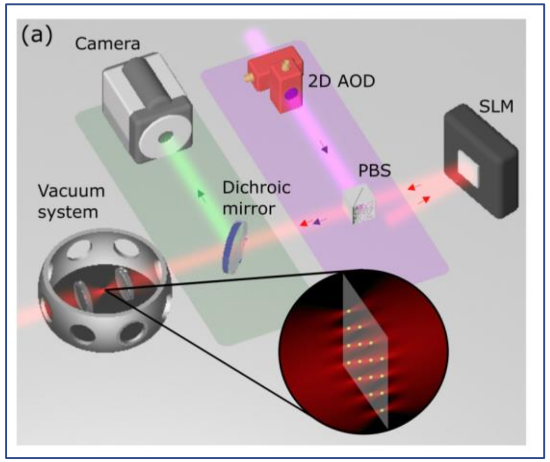
- The **aim** is to create an **integrated ecosystem**.

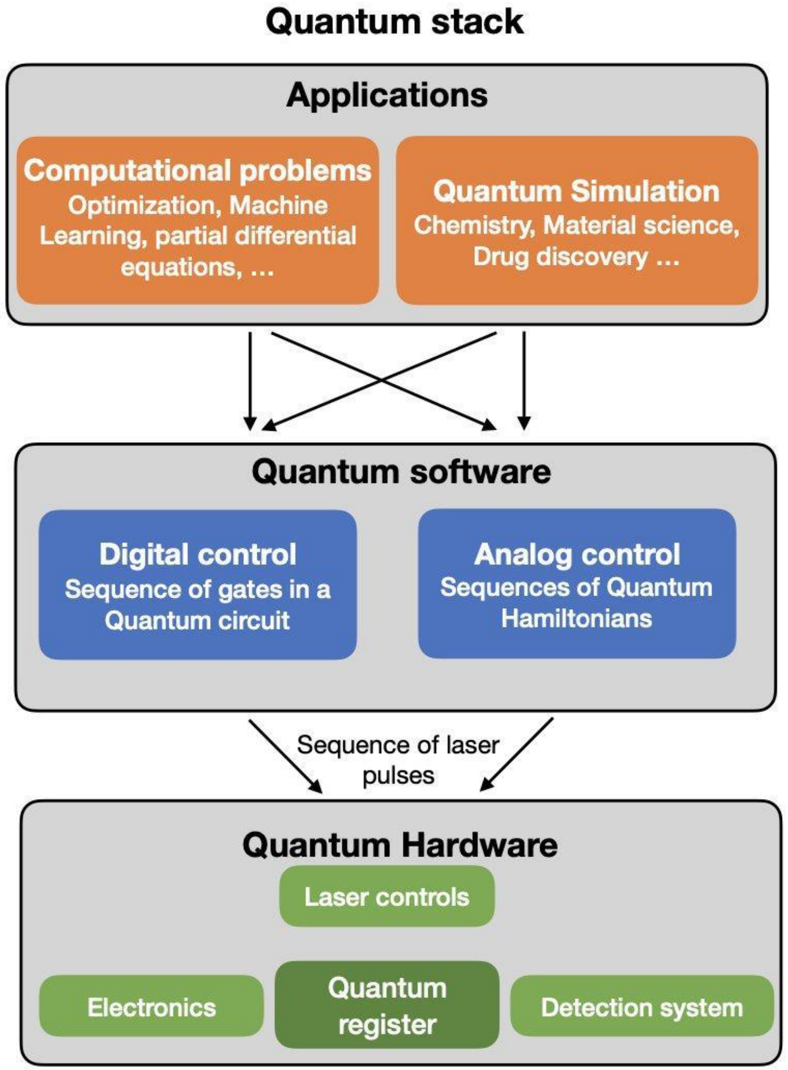
- **PASQAL** announced that it already has a **quantum simulator** with **100 qubits** (prototype 324-atom quantum processors scalable up to 1000).

Hybrid Ecosystem

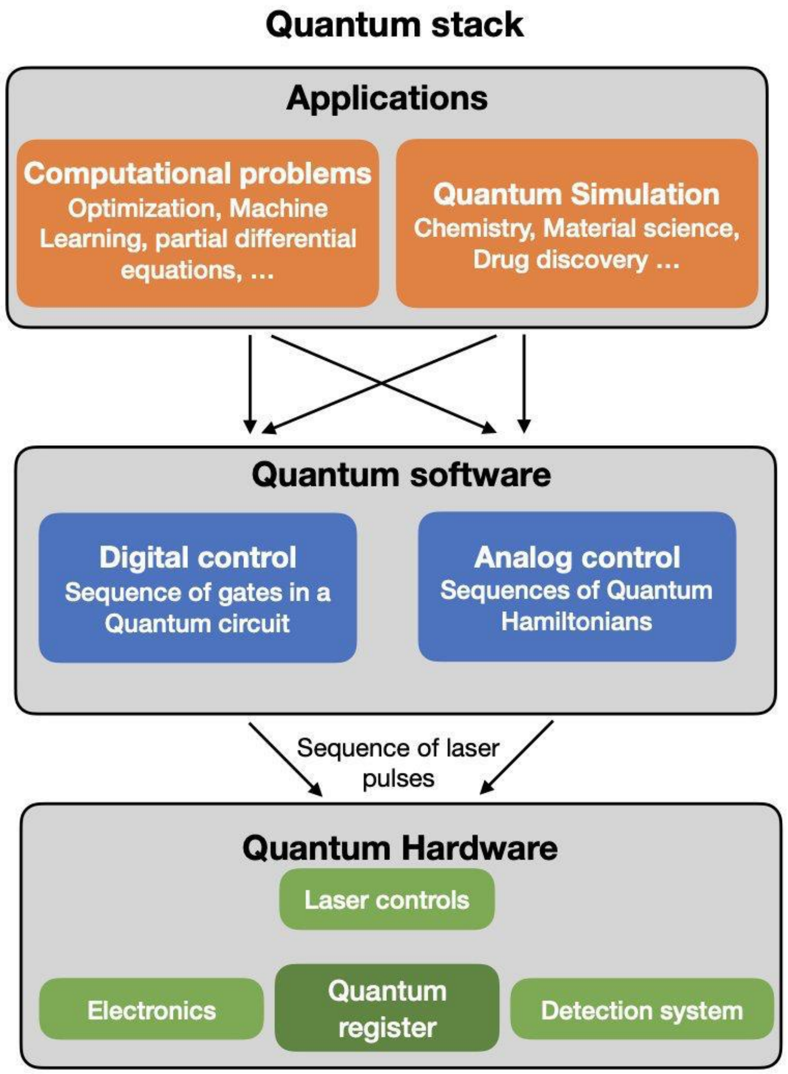
https://www.hpcqs.eu/

EuroHPC - HPCQS





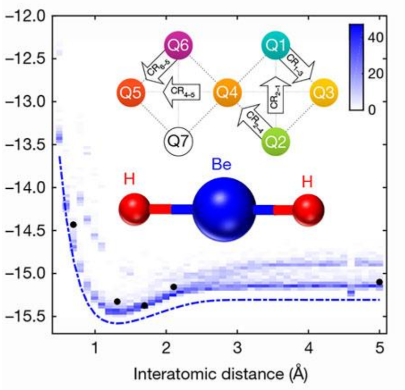
EuroHPC - HPCQS



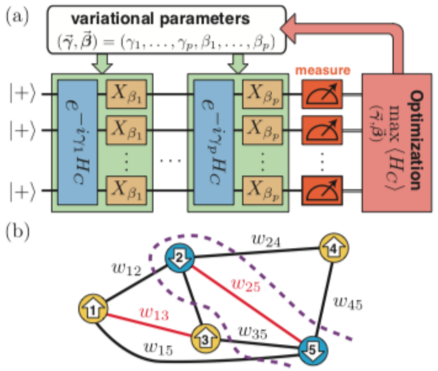
EuroHPC - HPCQS

NISQ Algorithms
(Noisy Intermidiate Scale Quantum)

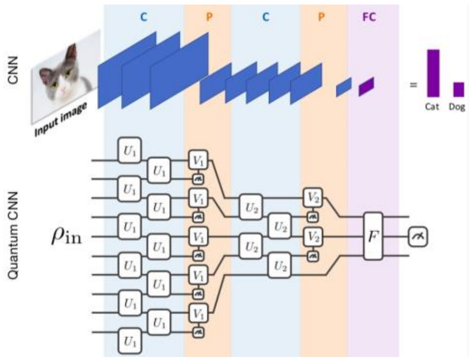
VQE



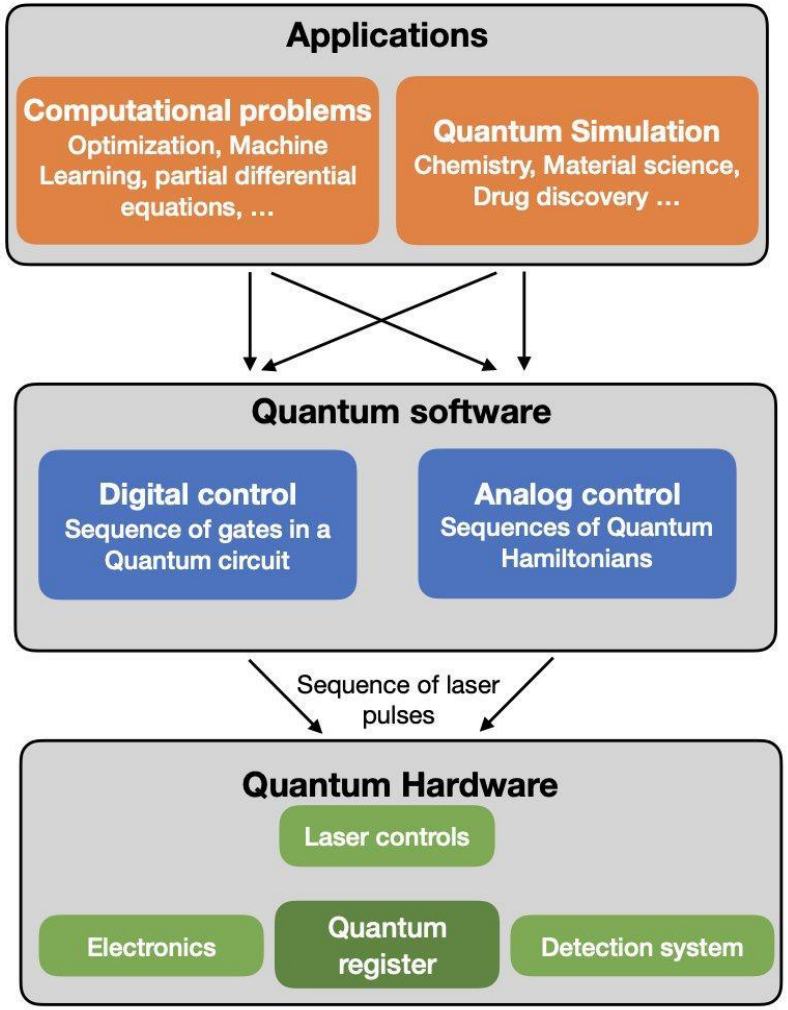
QAOA



QNN



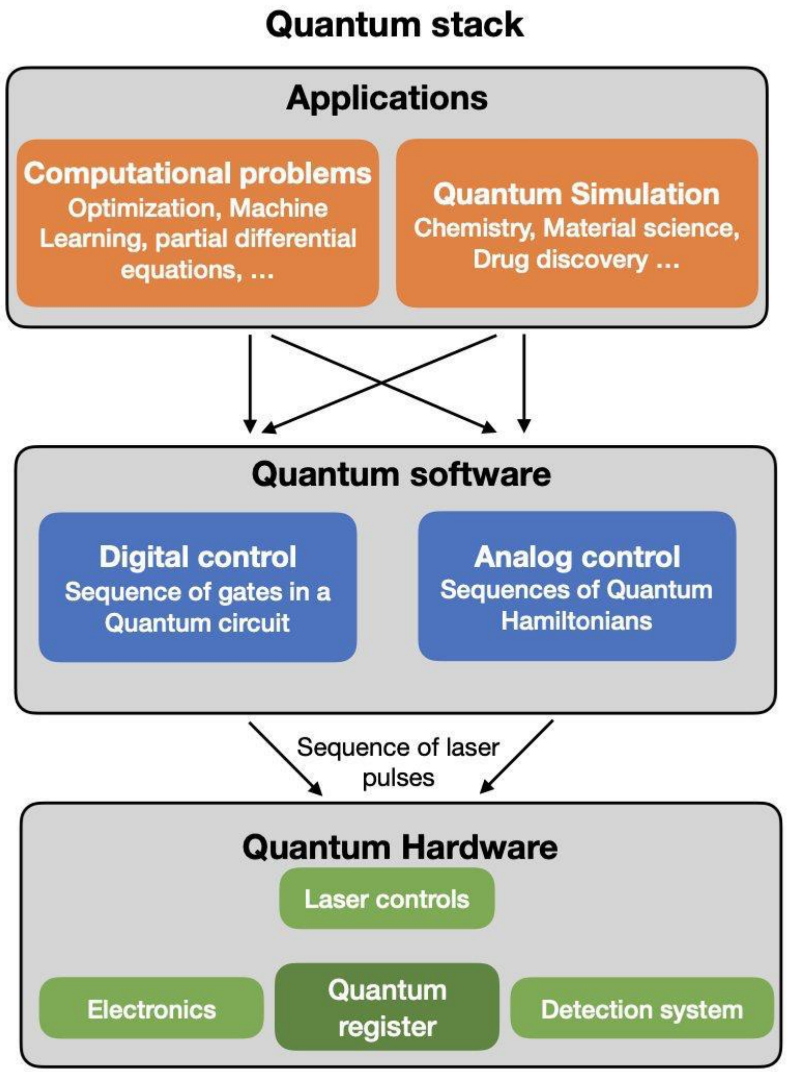
Quantum stack



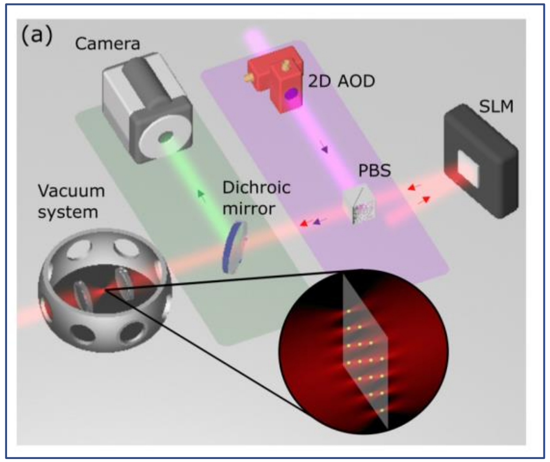
EuroHPC - HPCQS

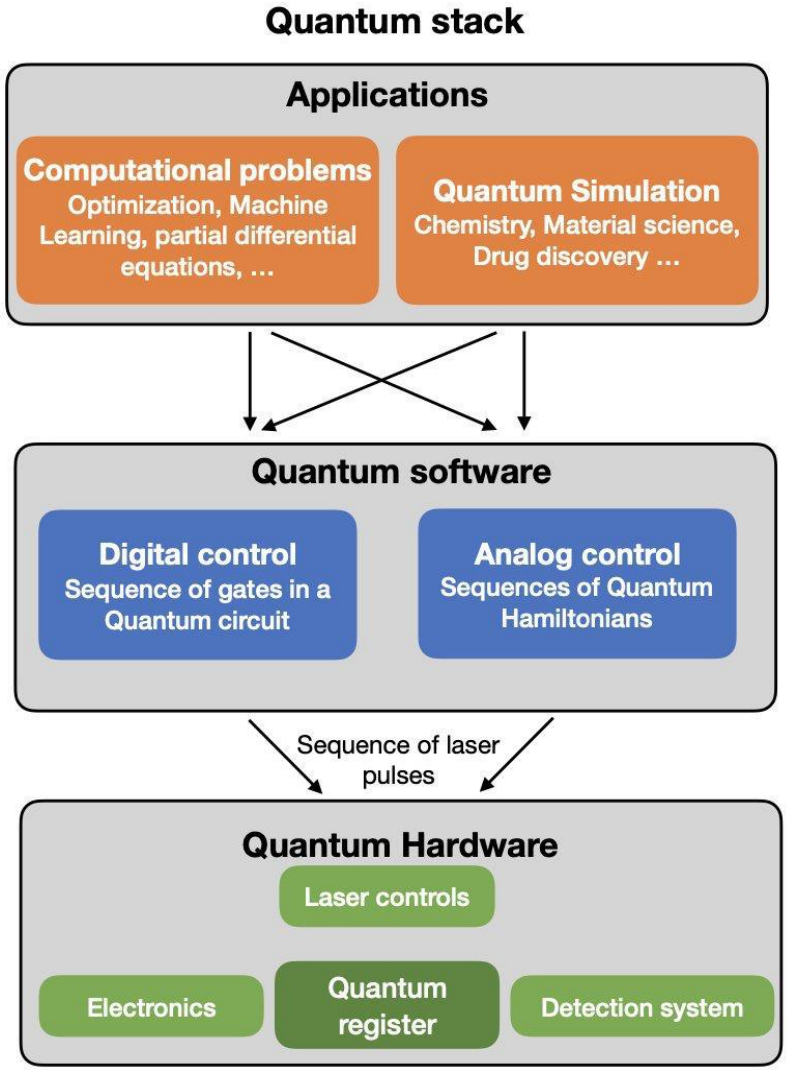
NISQ Algorithms
(Noisy Intermidiate Scale Quantum)

HPC



EuroHPC - HPCQS

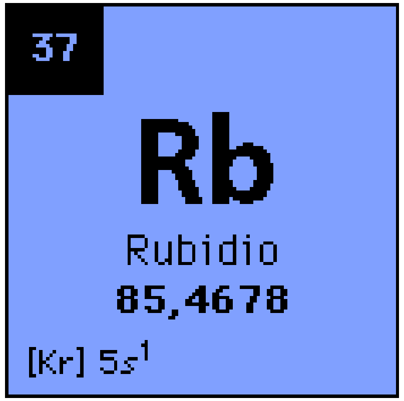




Pasqal Quantum Hardware: QC with Neutral Atoms

Pasqal Quantum Hardware: QC with Neutral Atoms

Pasqal employs **Rubidium Atoms** for its Neutral Atoms Quantum Computer



Rubidium: very **common** species in atomic physics that benefits from **well-established technological solutions**, especially in terms of **lasers**.

The **control of single atoms** as well as the **tuning** of their **interactions** has been achieved to a **high degree** in several laboratories.

Arranging ensembles of individual **(trapped) atoms separated by a few micrometers**

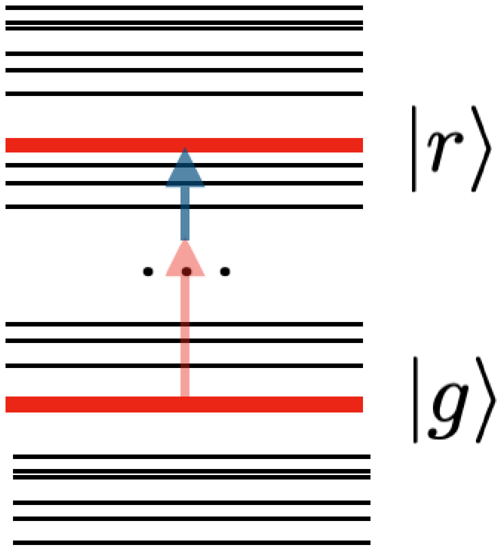
https://arxiv.org/pdf/2006.12326.pdf

Pasqal Quantum Hardware: QC with Neutral Atoms

Pasqal employs **Rubidium Atoms** in the construction of the **QPU**

Two electronic levels of the rubidium atoms are chosen to be the **two qubit states**

Since the number of **electronic states in an atom is infinite**, there are various possible choices for implementing the qubit



State of a Qubit
$\{|0\rangle, |1\rangle\}$

encoded in two electronic levels of the Rubidium Atom
$\{|g\rangle, |r\rangle\}$

Since the **atoms** are **indistinguishable**, even the **qubits are strictly identical**. This is a **great advantage** for obtaining **low error levels** when calculating.

https://arxiv.org/pdf/2006.12326.pdf

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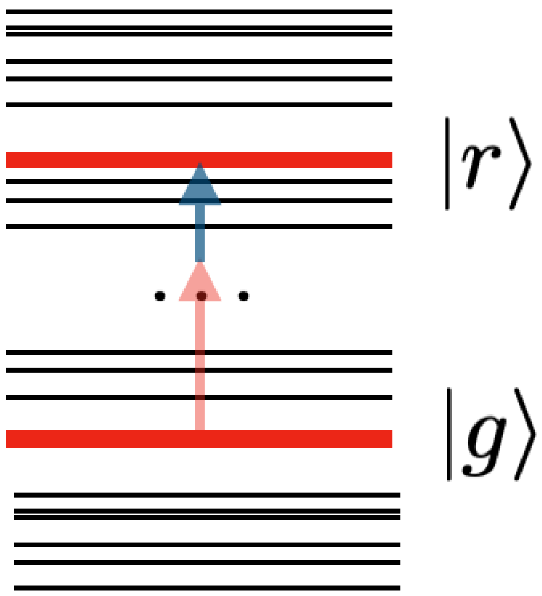
Pasqal Quantum Hardware: QC with Neutral Atoms

In order to generate interactions between them, they are excited by a resonant laser field to a **Rydberg level**, which has a large principal quantum number.



$\{|g\rangle, |r\rangle\}$ **are ground and «Rydberg» states characterized by:**

- **Long decay time:** if excited to the state $|r\rangle$, the atom tends to stay in that state and does not decays immediately in ground state $|g\rangle$
- **Strong interaction between atoms**

https://arxiv.org/pdf/2006.12326.pdf

Pasqal Quantum Hardware: QC with Neutral Atoms

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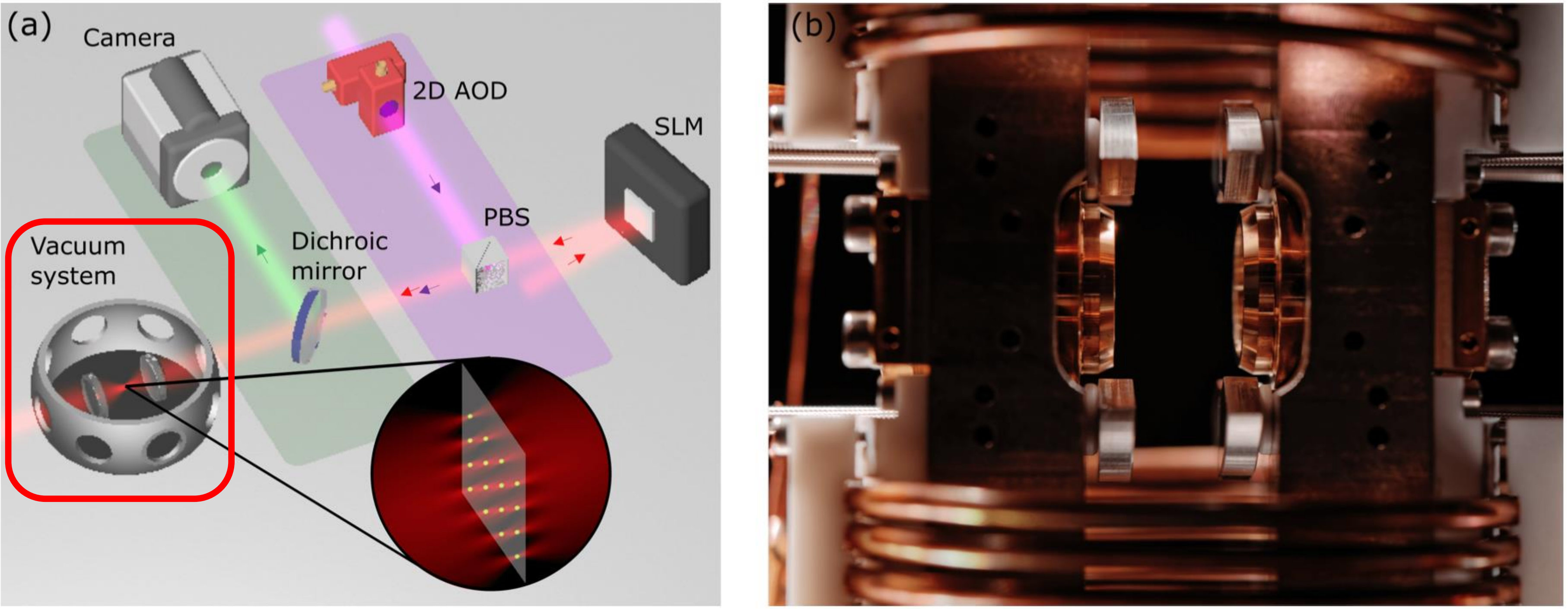
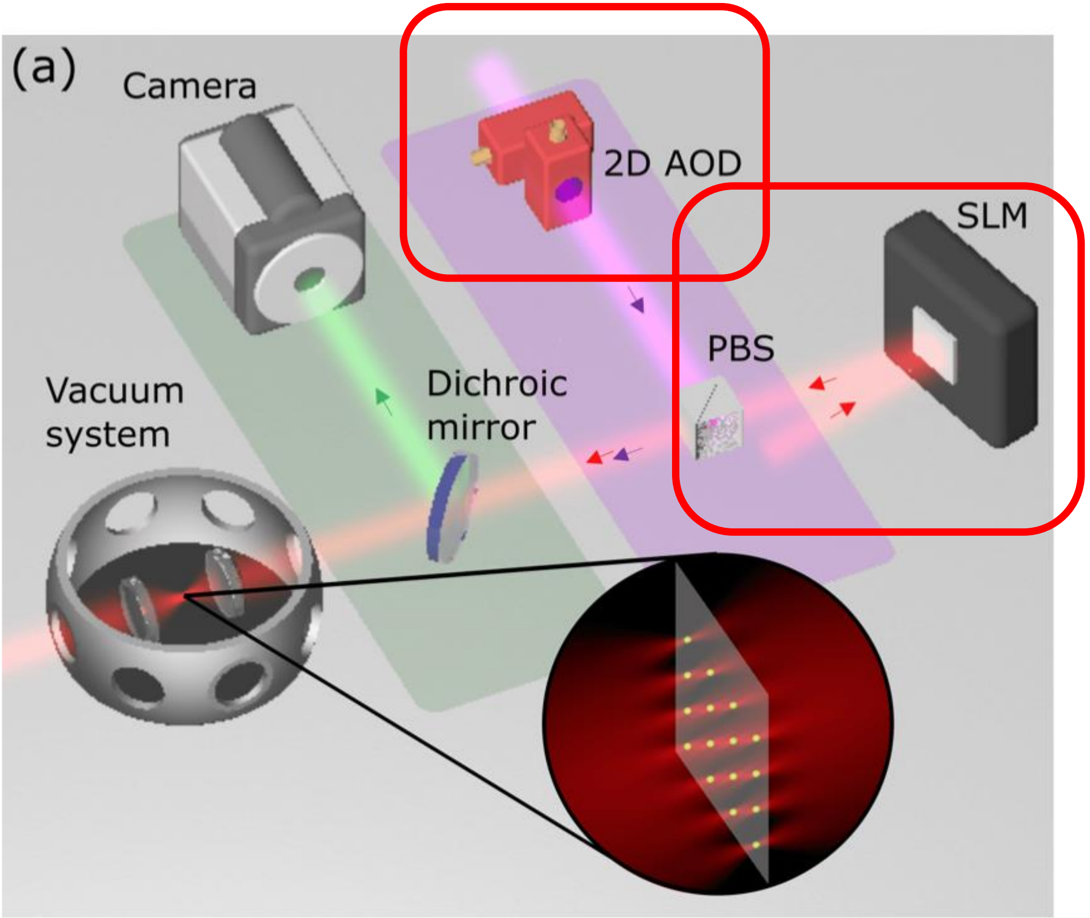


The atomic vapor is introduced into an ultra-high vacuum system operating at room temperature

https://arxiv.org/pdf/2006.12326.pdf

Pasqal Quantum Hardware: QC with Neutral Atoms



Rubidium atoms are trapped and held by laser beams, in particular:

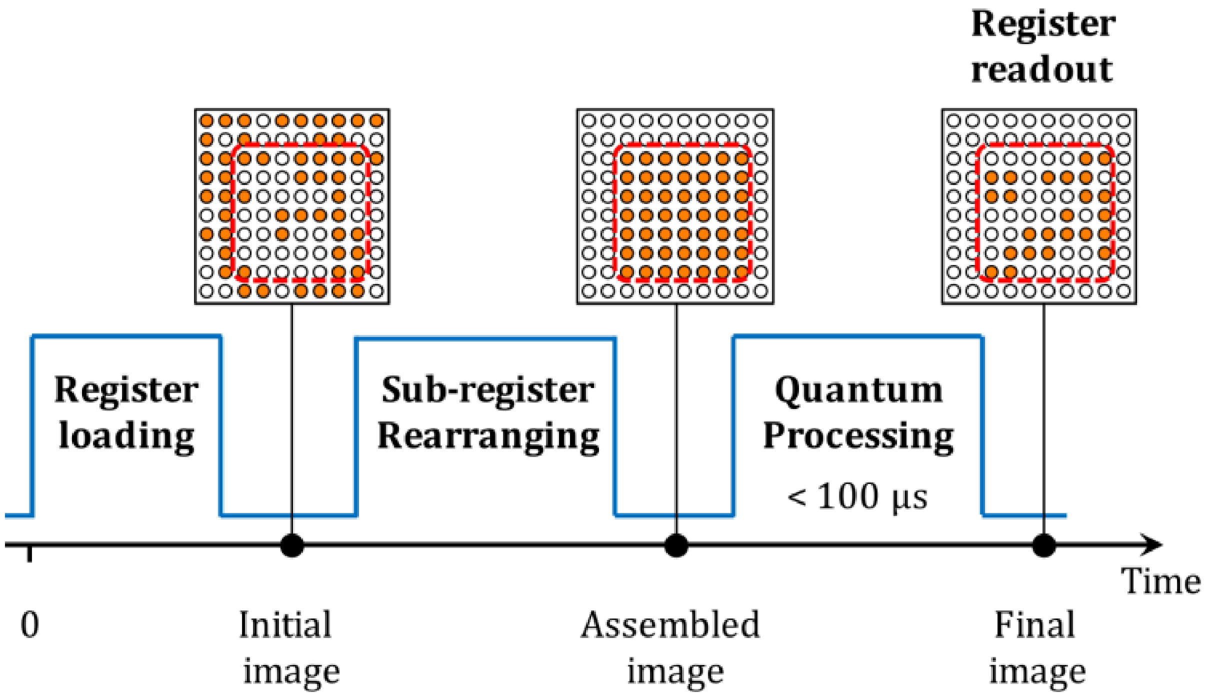
- **Optical Tweezers (purple beam)** controlled by 2D acousto-optic laser deflector (AOD)
- **Laser (red beam)** reflected by spatial light modulator (SLM) which gives the correct phase

Every Tweezers traps a single atom

https://arxiv.org/pdf/2006.12326.pdf

Pasqal Quantum Hardware: QC with Neutral Atoms

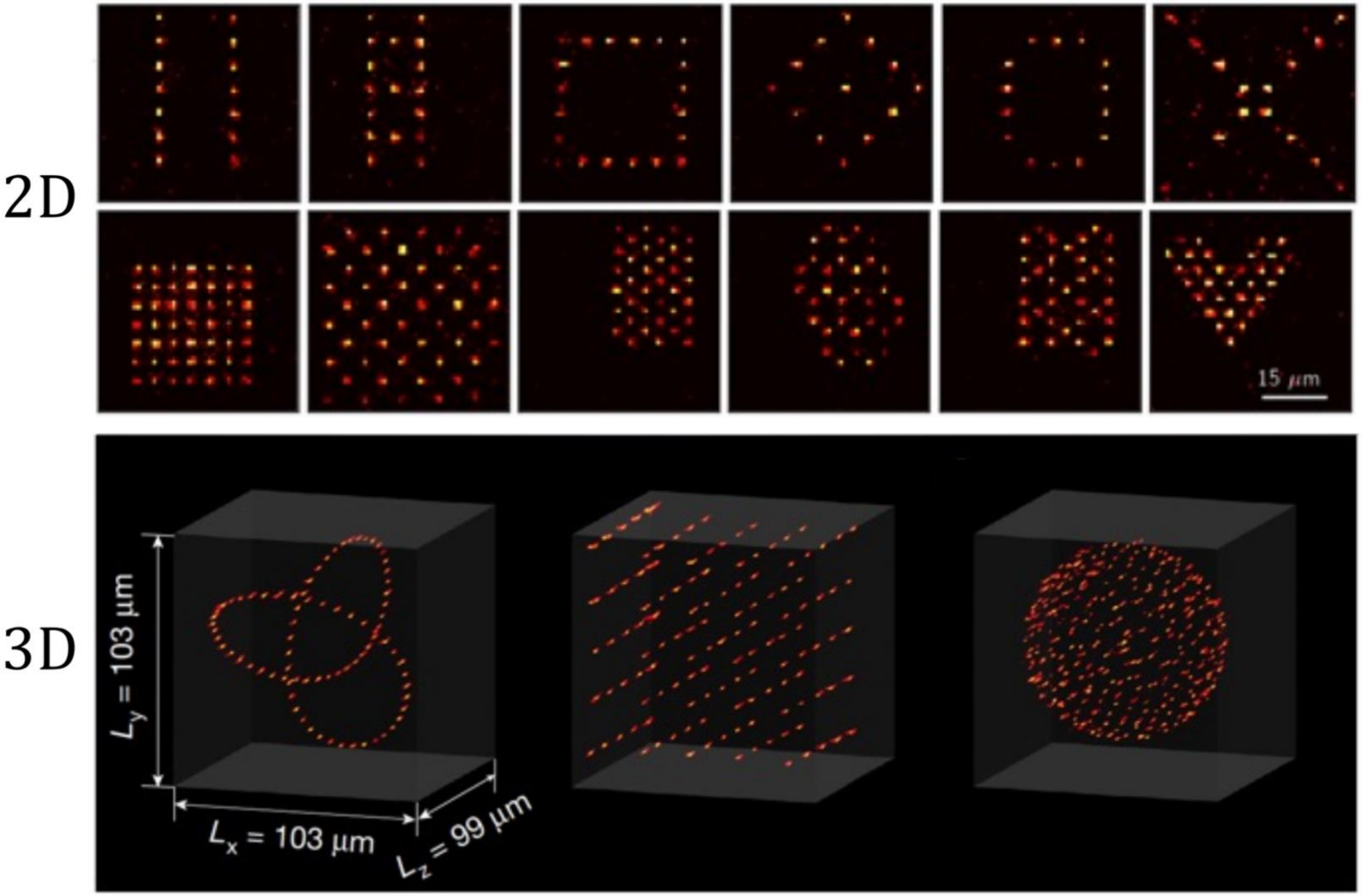
Temporal sequence of one computation cycle.



The **loading of the register being random**: here is a 50% chance that a single tweezer traps an atom

Atoms **are rearranged to obtain the desired topology**. This operation **takes less than 1 ms**.

Pasqal Quantum Hardware: QC with Neutral Atoms



By **moving** the **optical tweezers** it is possible to arrange the **topology** of the Rubidium atoms and therefore of the qubits

Depending on the application, it is useful to vary the Topology which can be 1D, 2D or even 3D

https://arxiv.org/pdf/2006.12326.pdf

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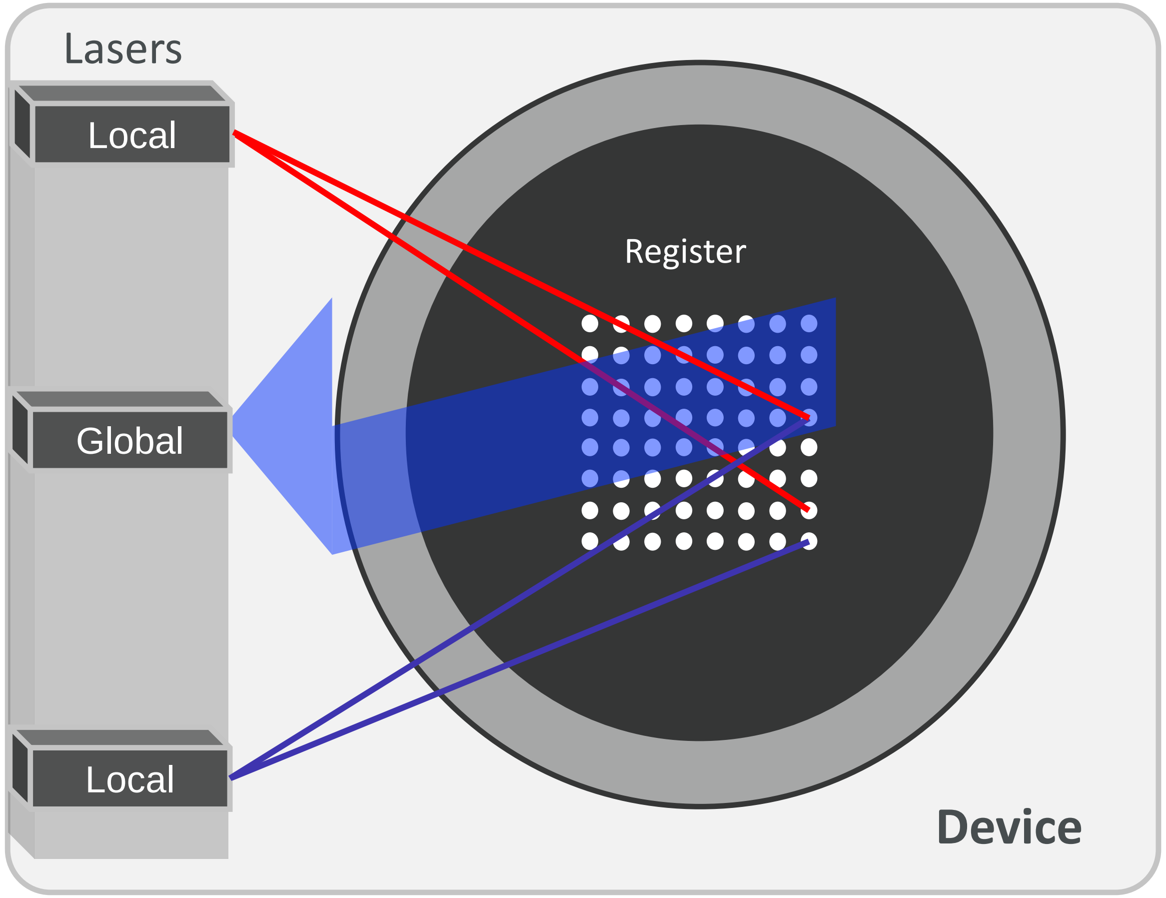
Pasqal Quantum Hardware: QC with Neutral Atoms



How quantum computation?

Lasers are responsible for manipulating the state of the atoms by addressing specific electronic transitions.

Local and global laser beams control the state of qubit registers and allow to:

- **Act on single qubit**

  e.g. $|g\rangle \rightarrow |r\rangle$

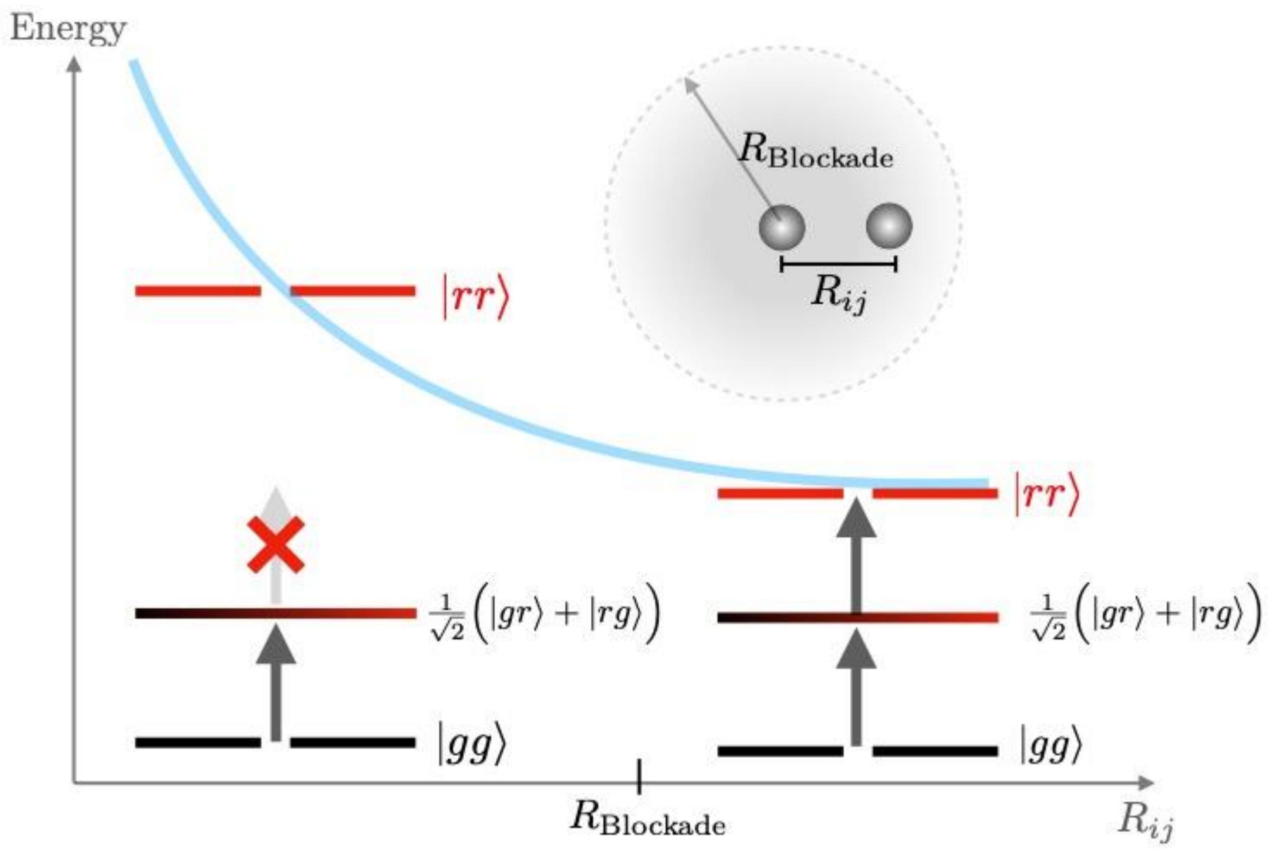
- **Make qubit interact**

  e.g. $|gg\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|gr\rangle + |rg\rangle\right)$

https://arxiv.org/pdf/2006.12326.pdf

Pasqal Quantum Hardware: QC with Neutral Atoms

Rydberg Blockade: principle used to create entanglement



The **interaction between two atoms** at **distance R** and at the same Rydberg level is described by the **Van der Waals force**, which scales as R^{-6}

The interaction within this radius is strong enough to make the **state $|\mathbf{rr}\rangle$ inaccessible**

If the atoms are excited simultaneously, the resulting state is an **entangled state.**

https://arxiv.org/pdf/2006.12326.pdf

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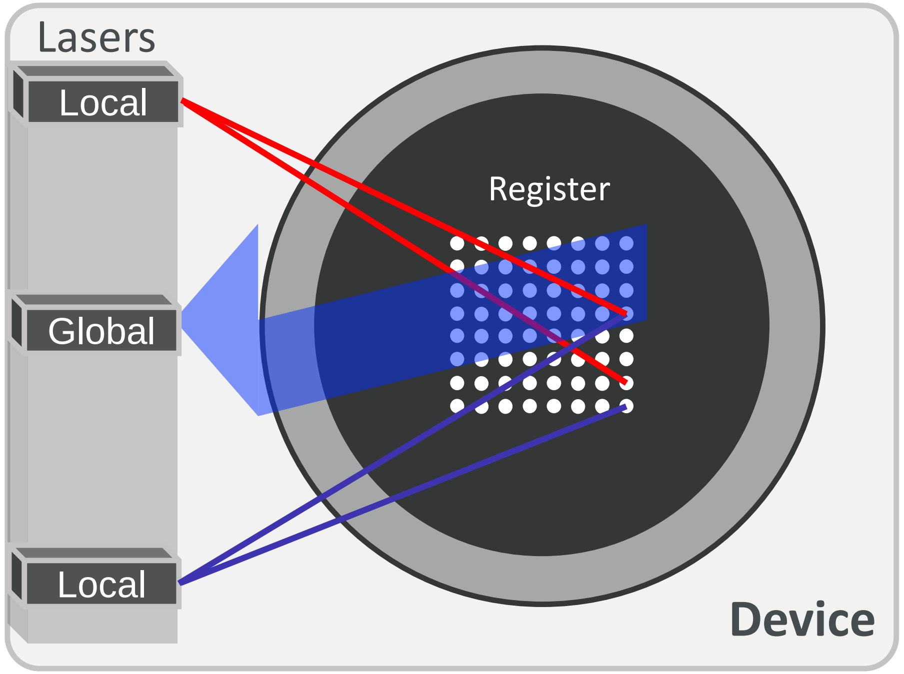
Pasqal Quantum Hardware: QC with Neutral Atoms



Mathematically, **lasers** interact with qubits, **modifying** the **Hamiltonian**, which is a function that describes the **energy** of the entire **qubit system**

$$H = \frac{\hbar\Omega(t)}{2}\sum_i \sigma_i^x - \frac{\hbar\delta(t)}{2}\sum_i \sigma_i^z + \sum_{i<j} U_{ij} n_i n_j$$

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Pasqal Quantum Hardware: QC with Neutral Atoms

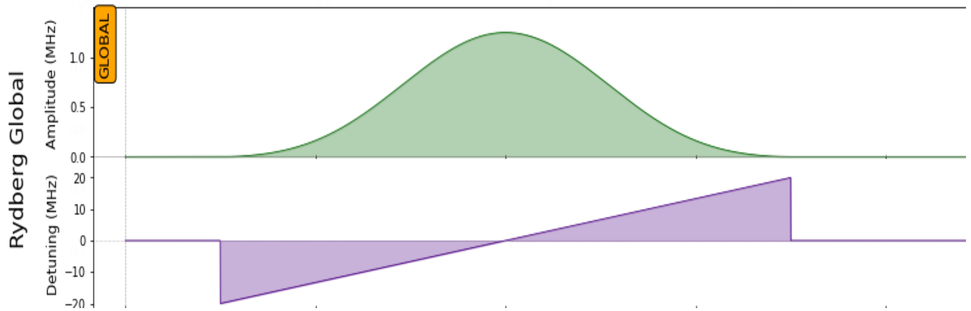
$$H = \frac{\hbar\Omega(t)}{2}\sum_i \sigma_i^x - \frac{\hbar\delta(t)}{2}\sum_i \sigma_i^z + \sum_{i<j} U_{ij} n_i n_j$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\hat{n}_j = (\mathbb{I} + \sigma_j^z)/2$$

Rabi Frequency **Detuning**

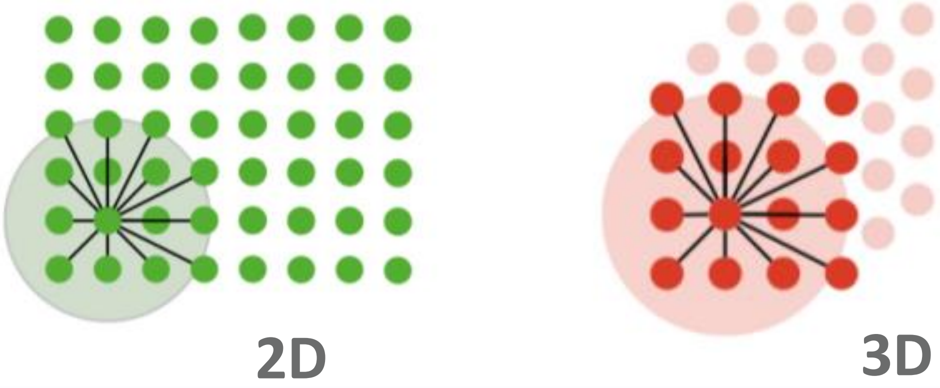
They vary by changing the **intensity** and **frequency** of the laser



$$U_{ij} = \frac{C_6}{r_{ij}^6}$$

Modulates interaction between qubits

Vary with **Topology**



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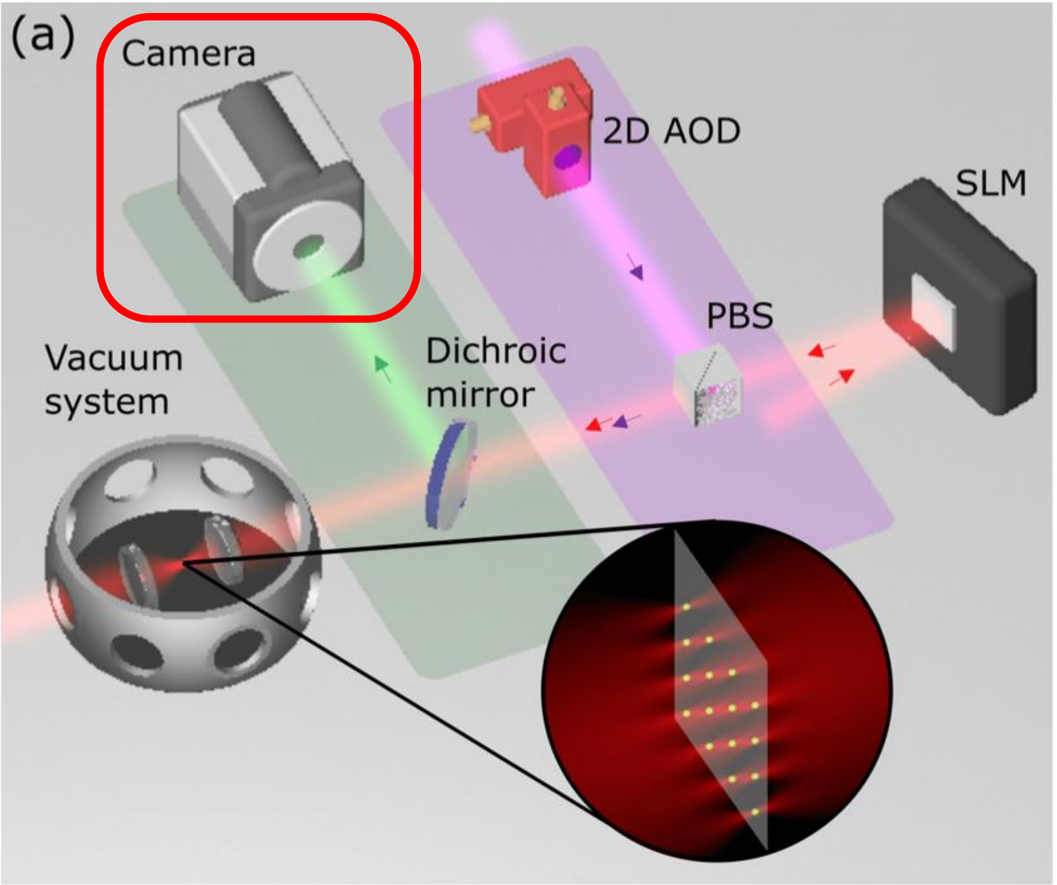


At the **end of the computation**, the qubit register is **measured** by **observing the final fluorescence image** (green beam).

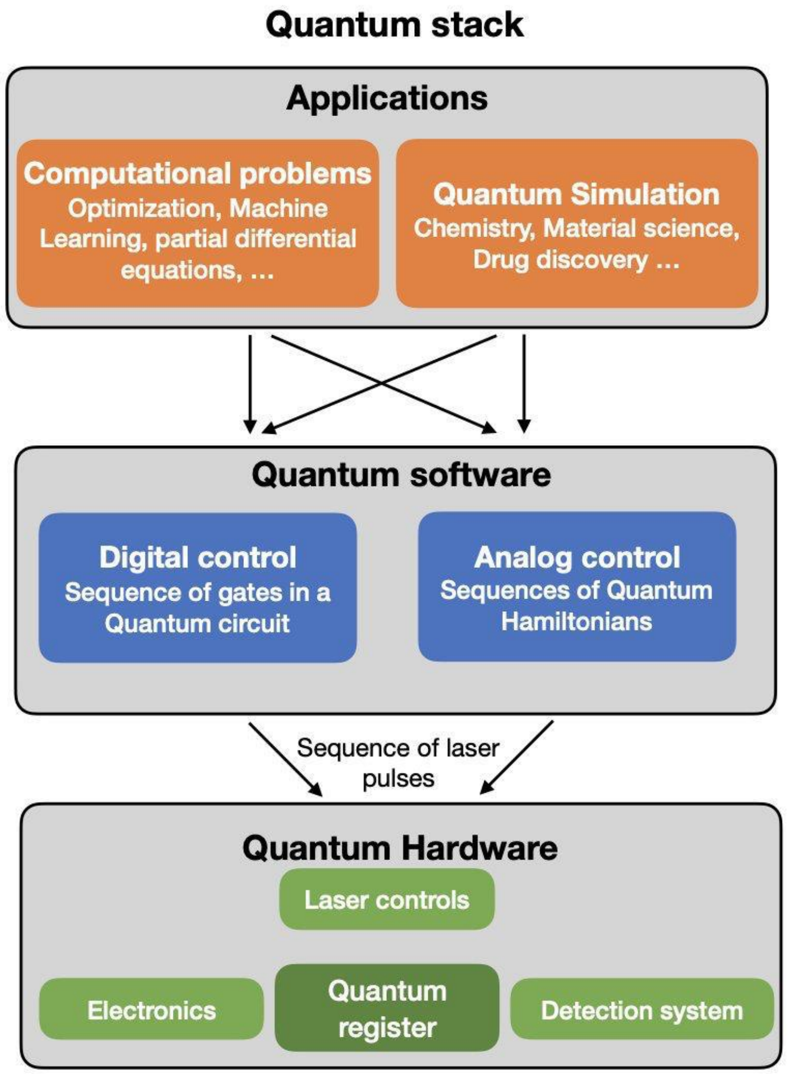
The measurement process is performed in such a way that **each atom in the qubit state | 0⟩ appears bright,** while **the atoms in the qubit state | 1⟩ remain dark**.

https://arxiv.org/pdf/2006.12326.pdf

EuroHPC - HPCQS

Pulser

Cirq

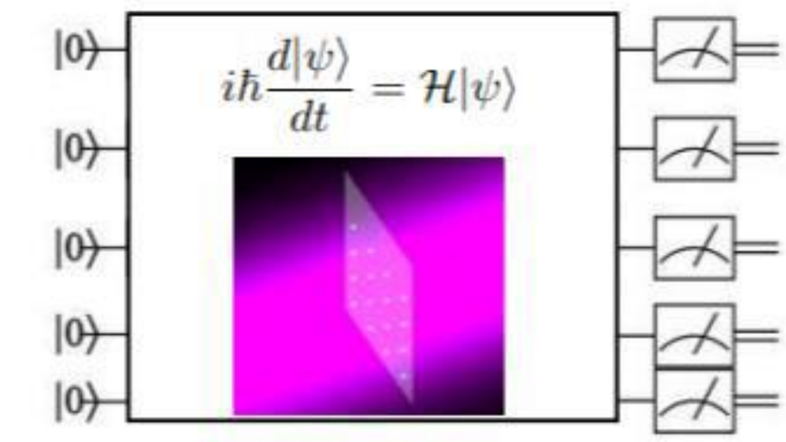


Pulser: Control Software for Pasqal QC

Pulser: Control Software for Pasqal QC

Lower level programming

(b) Analog processing



Pulser

Quantum computing is carried out by **directly manipulating** the mathematical operator (**Hamiltonian**) that **describes the evolution** of the **quantum system**

$$H = \sum_i \frac{\hbar}{2}\left(\Omega(t)\sigma_i^x - \delta(t)\sigma_i^z\right) + \sum_{i<j} U_{ij}\hat{n}_i\hat{n}_j$$

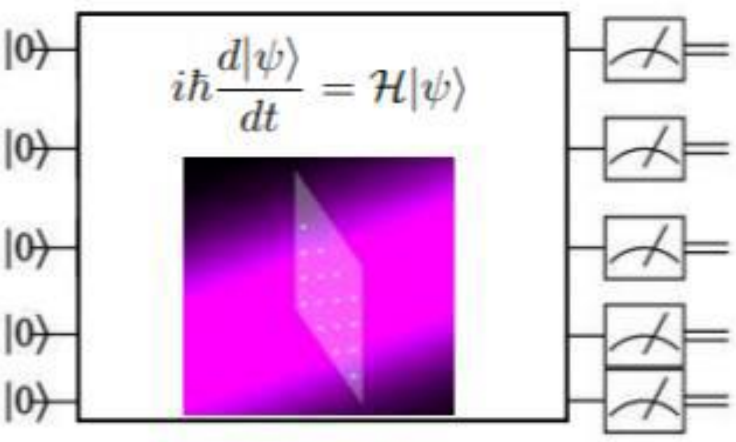
Possible by **varying**:

- **Intensity** and **frequency** of lasers
- Qubit register **topology**

Pulser: Control Software for Pasqal QC

Lower level programming

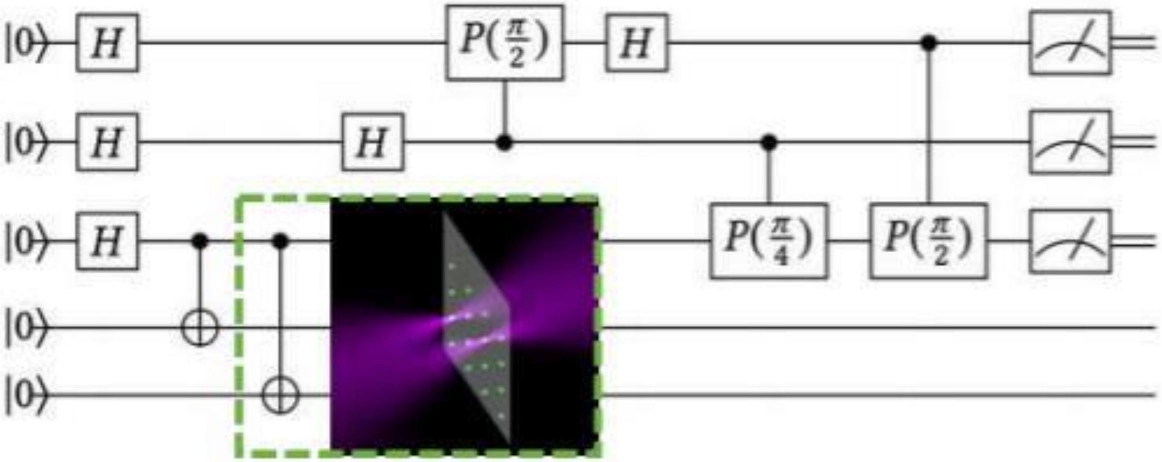
(b) Analog processing



Pulser

Higher level programming

(a) Digital processing



Cirq

Pulser: Control Software for Pasqal QC

Pulser

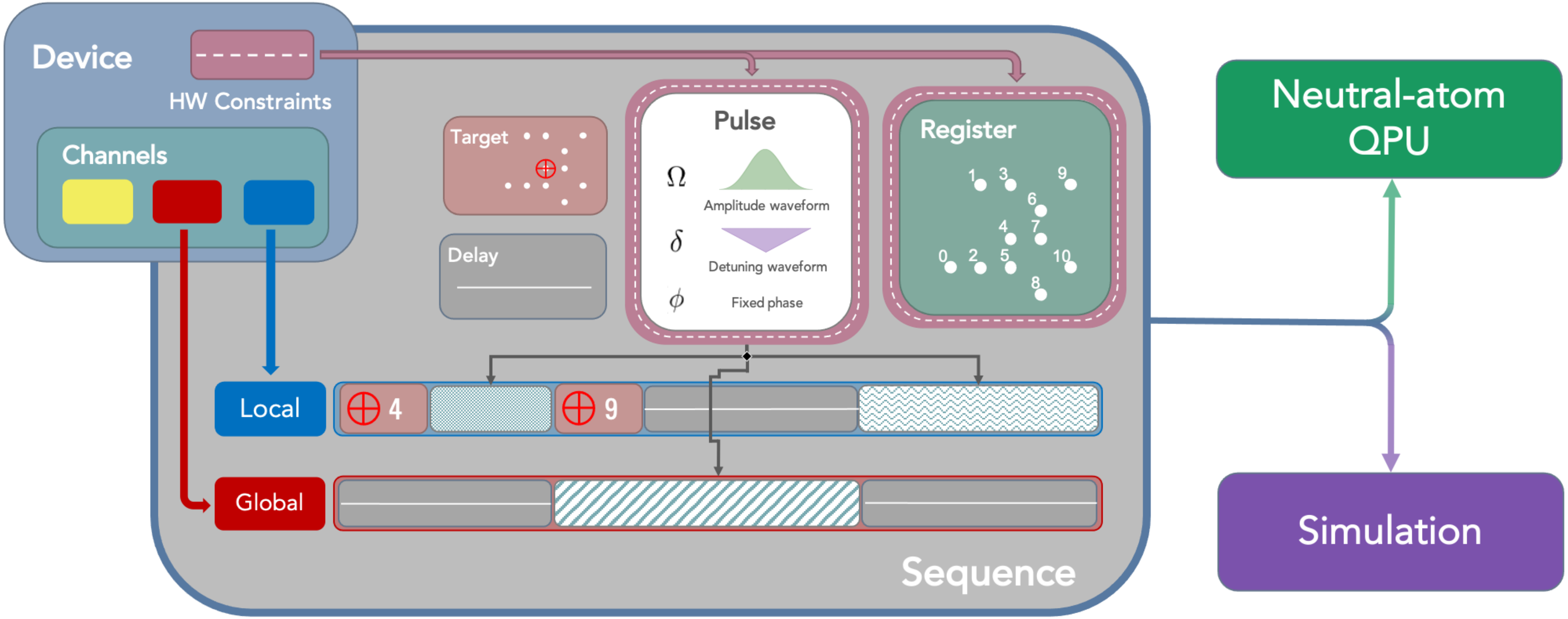
Python software library for **programming Pasqal devices** at the **laser pulse level**.

It allows to **design pulse sequences** that represent the physical parameters relevant to the computation.

The **sequences** can be **read** and **executed** by the **QPU** or by an **emulator**

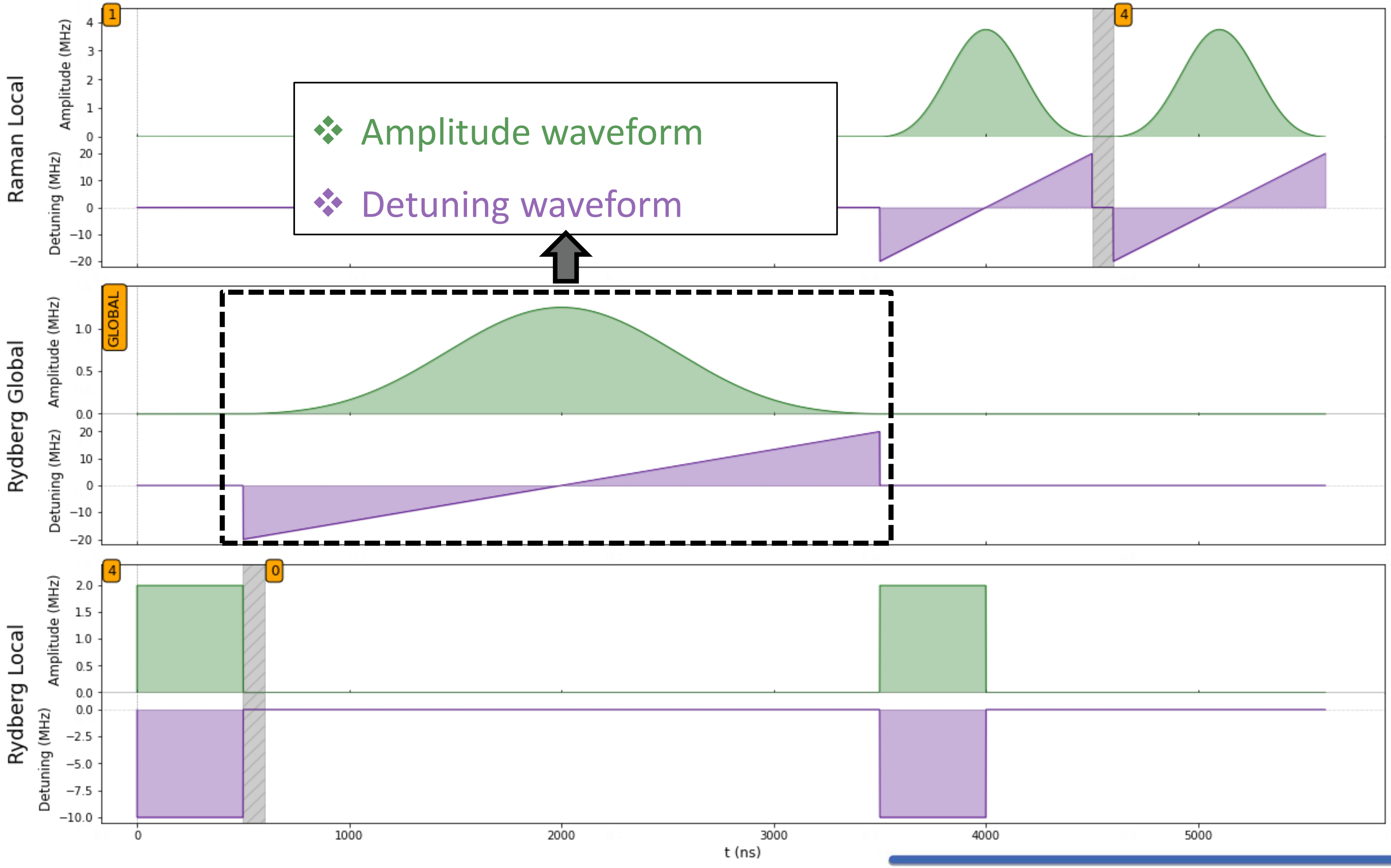
Pulser: Control Software for Pasqal QC

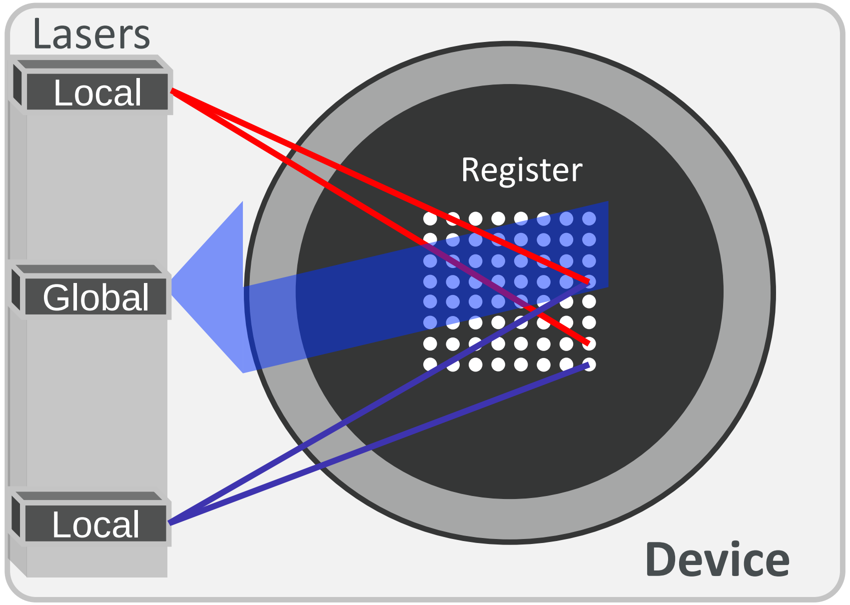
In Pulser, local and global pulse sequences can be defined



Pulser: Control Software for Pasqal QC

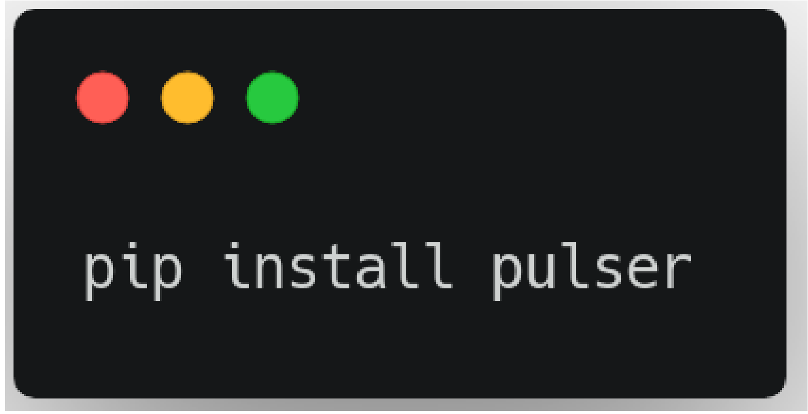
Practice Session

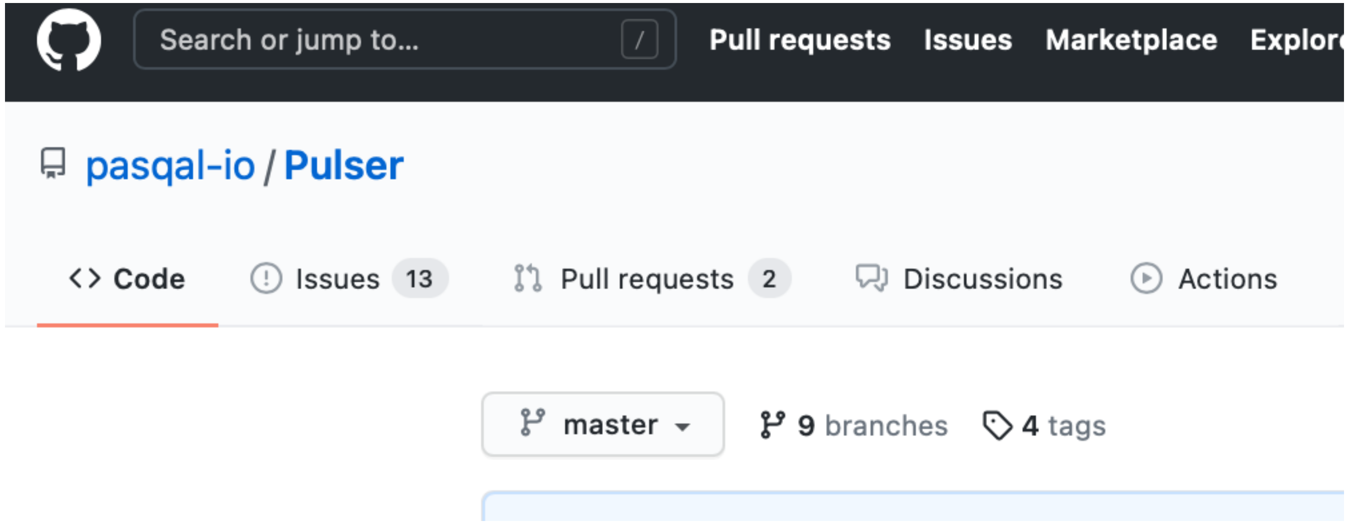




Pulser: Control Software for Pasqal QC

Practice Session





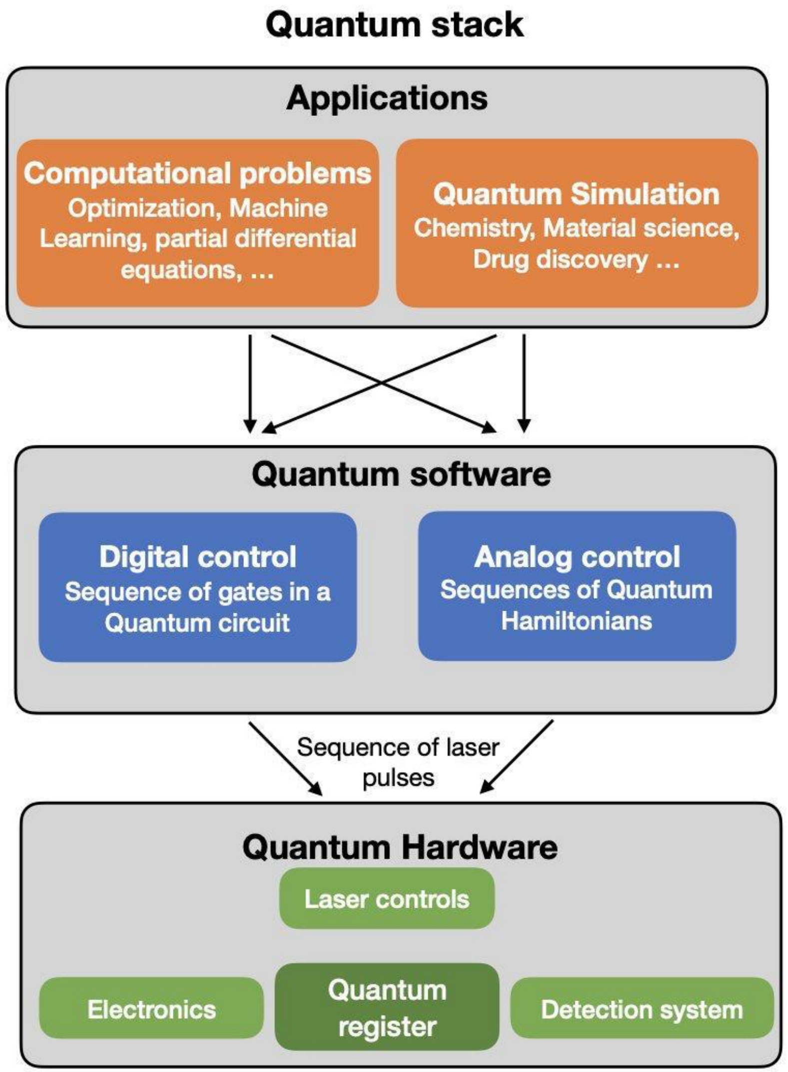
https://github.com/pasqal-io/Pulser

https://pulser.readthedocs.io/en/stable/

Pulser: Control Software for Pasqal QC

NISQ Algorithms
(Noisy Intermidiate Scale Quantum)

HPC

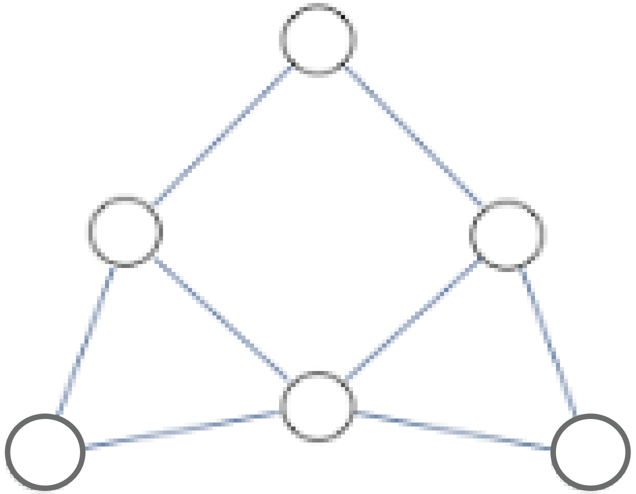


Application: QAOA & MIS problem

Application: QAOA & MIS problem

Maximal Independent Set (MIS) Problem

Definition: Given a graph, **color** the **largest number of nodes avoiding** that **nodes of the same color** are **connected** together



It is a hard **combinatorial optimization problem** (complexity class **NP-hard**)

Applications:

- Modeling and Optimization in Massive Datasets
- Modeling Wireless Networks
- Matching Molecular Structures

Maximal Independent Set (MIS) Problem

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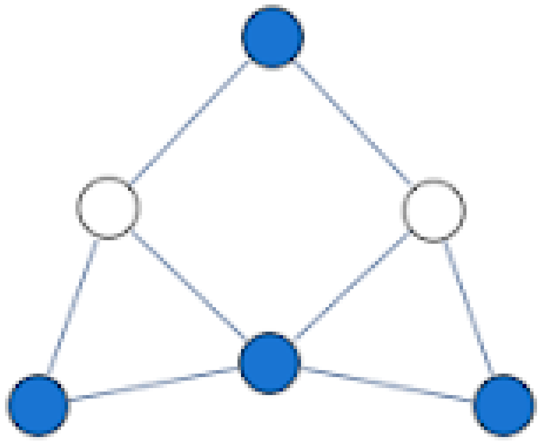
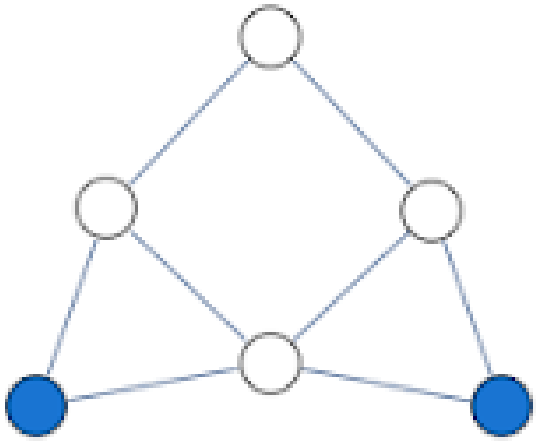
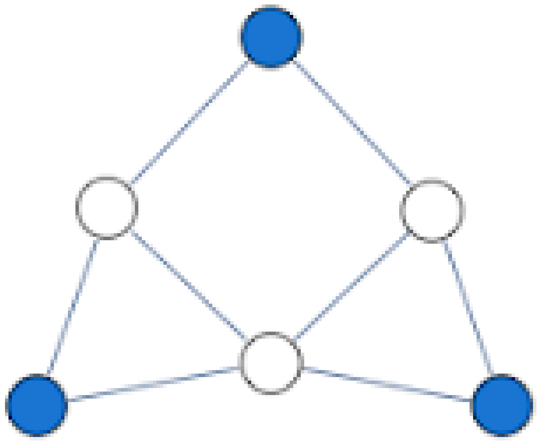


Not an independent set



Independent set but on maximal



Maximal Independent Set

Maximal Independent Set (MIS) Problem

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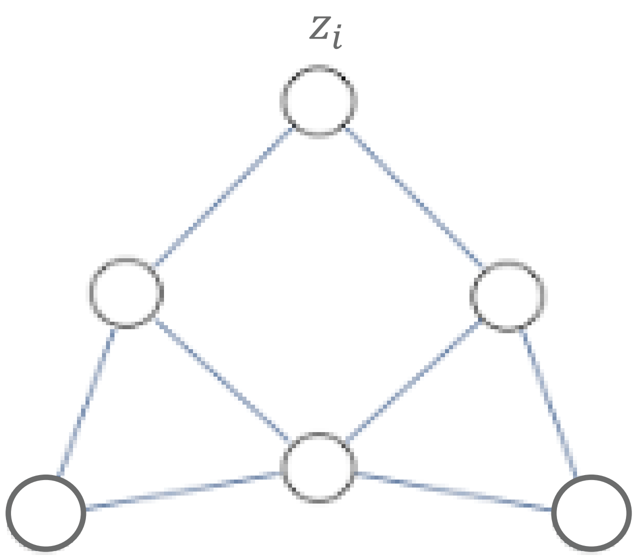


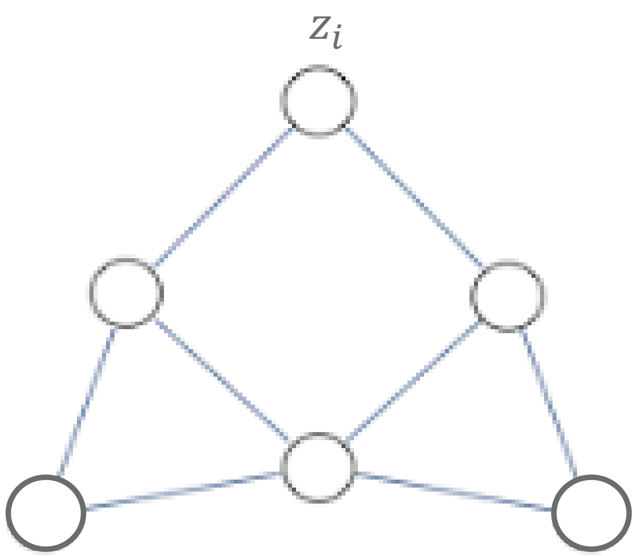
Combinatorial formulation

We can attribute a binary variable z_i to each node, where z_i = 1 if node i is colored (therefore it belongs to the independent set) and z_i = 0 otherwise.

Application: QAOA & MIS problem

Maximal Independent Set (MIS) Problem

<u>Definition</u>: Given a graph, **color** the **largest number of nodes avoiding** that **nodes of the same color** are **connected** together



The **Maximum Independent Set** corresponds to the **minimum** of the following **cost function:**

$$C(z_1, \ldots, z_N) = -\sum_{i=1}^{N} z_i + U \sum_{\langle i,j \rangle} z_i z_j$$

$$U \gg 1$$

Application: QAOA & MIS problem

Maximal Independent Set (MIS) Problem

QAOA Ansatz

$$\underbrace{|\boldsymbol{\gamma}, \boldsymbol{\beta}\rangle}_{\text{solution}} = \underbrace{U(B, \beta_p) U(C, \gamma_p) \cdots U(B, \beta_1) U(C, \gamma_1)}_{\text{Circuit (alternating circuits)}} \underbrace{|s\rangle}_{\text{initial state}}$$

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solution — Circuit (alternating circuits) — initial state

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$$U(B,\beta) = e^{-i\beta B} = \prod_{j=1}^{n} e^{-i\beta\sigma_j^x}$$

Application: QAOA & MIS problem

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$$C(z_1,\ldots,z_N) = -\sum_{i=1}^{N} z_i + U \sum_{\langle i,j\rangle} z_i z_j$$

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Pulser

$$H = \sum_{i=1}^{N} \frac{\hbar\Omega}{2}\sigma_i^x - \sum_{i=1}^{N} \frac{\hbar\delta}{2}\sigma_i^z + \sum_{j<i} \frac{C_6}{|\mathbf{r}_i - \mathbf{r}_j|^6} n_i n_j .$$

Application: QAOA & MIS problem

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Practice Session

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https://www.quantumcomputinglab.cineca.it

r.mengoni@cineca.it
Linkedin

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