Pasqal Defining the quantum reality

Q-KHAI Quantum Simulation

Part 1:

양자컴퓨팅 소개 / 중성원자 양자컴퓨터 /
Pasqal 소프트웨어 스택 / Pulser Studio 실습

Woojun Lee, Ph. D.
Technical Business Developer, Pasqal
Aug. 3, 2025

Contents

Pasqal

Part 1 (3, Mon) 1:30 pm

- 양자컴퓨팅 소개
- 중성원자 양자컴퓨터
- Pasqal 소프트웨어 스택
- Pulser Studio 실습

Part 2 (3, Mon) 2:30 pm

- 중성원자 양자 시뮬레이션 (Spin sytems, AFM states, Direct quantum simulation)
- 실습 (Pulser, 양자시뮬레이션)

Part 3 (4, Tue) 9 am

- MIS, QUBO theory, use cases, sdk
- QEK theory, use cases, sdk
- 실습 (QUBO, QEK)

Pasqal Defining the quantum reality

양자컴퓨팅 소개

양자컴퓨터의 필요성

Pasqal

$$10^{60} \approx 2^{200}$$

중간 정도 복잡한 분자의 양자 상태를 정확하게 나타내기 위해 관련된 전자, 진동, 스핀 자유도를 모두 고려할 때, 필요한 상태 벡터는 $10^{60} \approx 2^{200}$ 에 근접하는 차원을 갖는 힐베르트 공간이 필요.

10^{60} 개의 숫자를 저장하려면 전 지구를 고전 데이터 센터로 채워도 충분하지 않음

양자컴퓨터를 사용하면 200개의 큐비트로 가능

4

양자컴퓨터 - **자연 자체를 모방하는 계산 기계**

Pasqal

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

about what the computer was, we can say: Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws. Or we can turn the other way and say: Let the computer still be the same kind that we thought of before—a logical, universal automaton; can we imitate this situation? And I'm going to separate my talk here, for it branches into two parts.

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

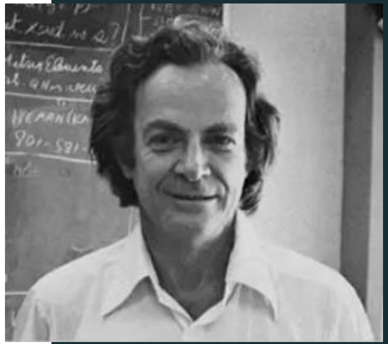
The first branch, one you might call a side-remark, is, Can you do it with a new kind of computer—a quantum computer? (I'll come back to the other branch in a moment.) Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind. If we disregard the continuity of space and make it discrete, and so on, as an approximation (the same way as we allowed ourselves in the classical case), it does seem to

양자컴퓨터

파인만의 주장: **자연 자체를 모방하는 계산 기계**

"만약 자연이 양자역학적으로 움직인다면,
자연을 정확히 시뮬레이션하는 컴퓨터도
양자역학을 따르지 않을까요??"

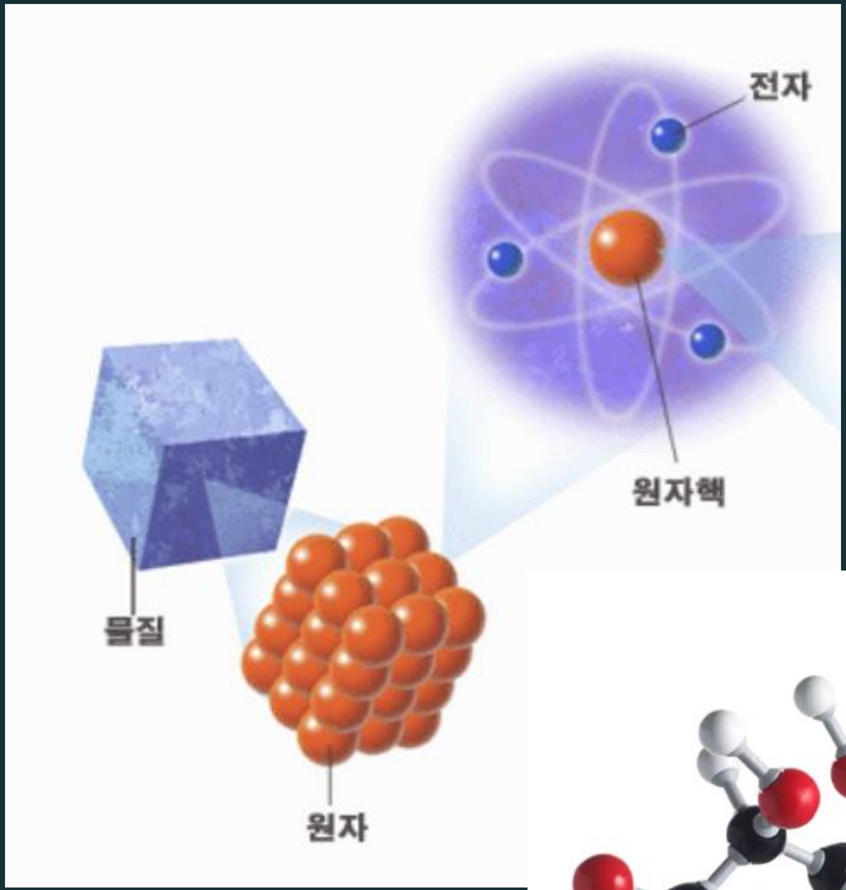
즉, **고전 컴퓨터로 양자 시스템을 시뮬레이션하는**
데는 근본적인 한계가 존재합니다. 그렇다면 컴퓨터
자체를 양자역학적 실체로 만들 수 있을까요?

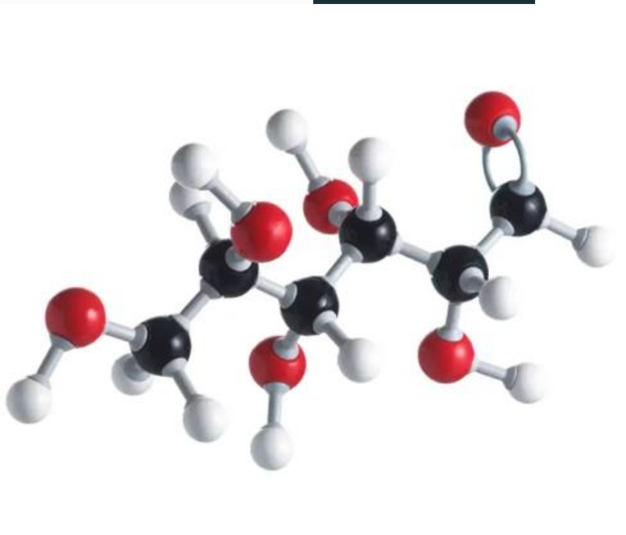


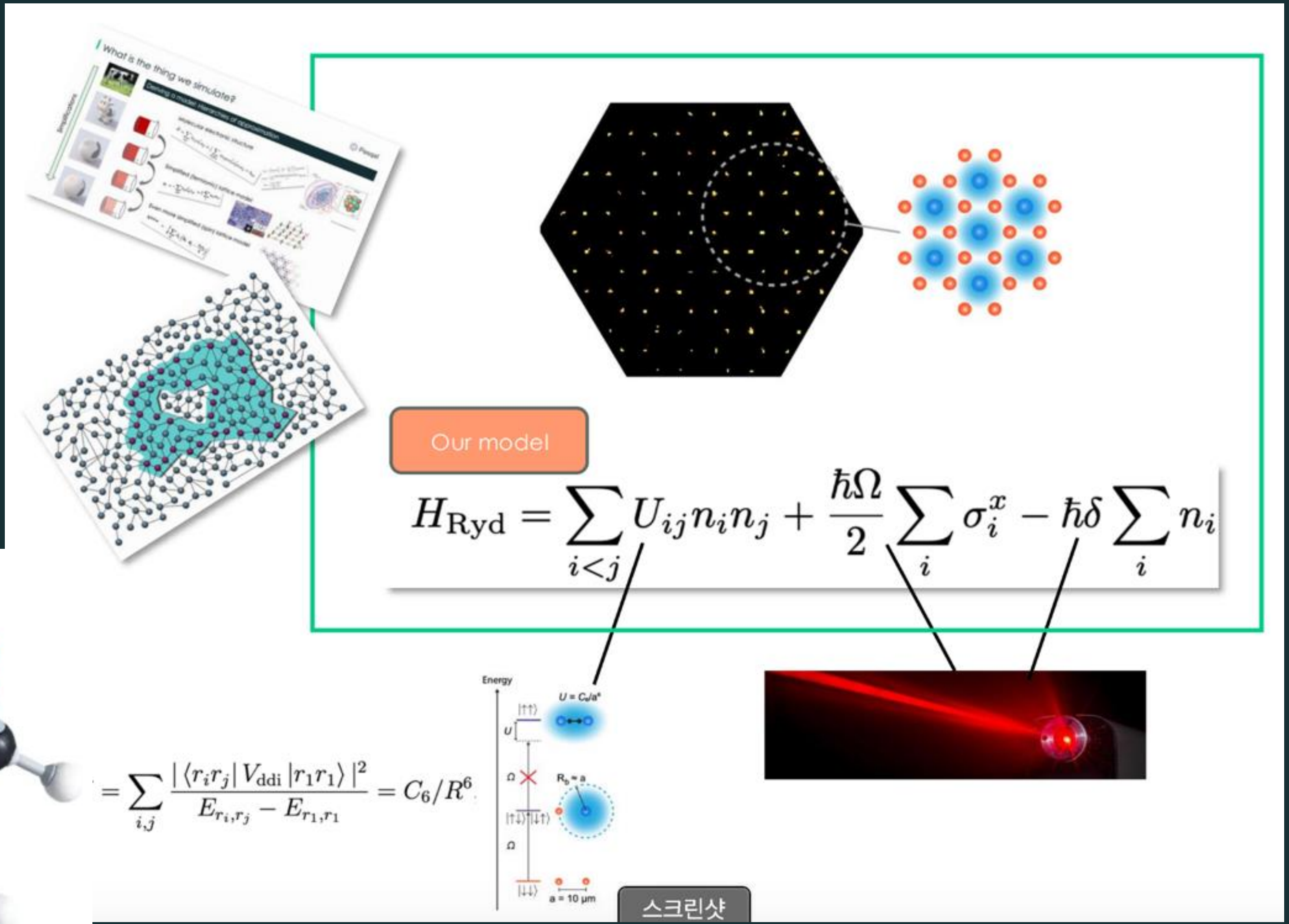
(Dr. Richard P. Feynman)

양자컴퓨터 - 자연 자체를 모방하는 계산 기계

Pasqal

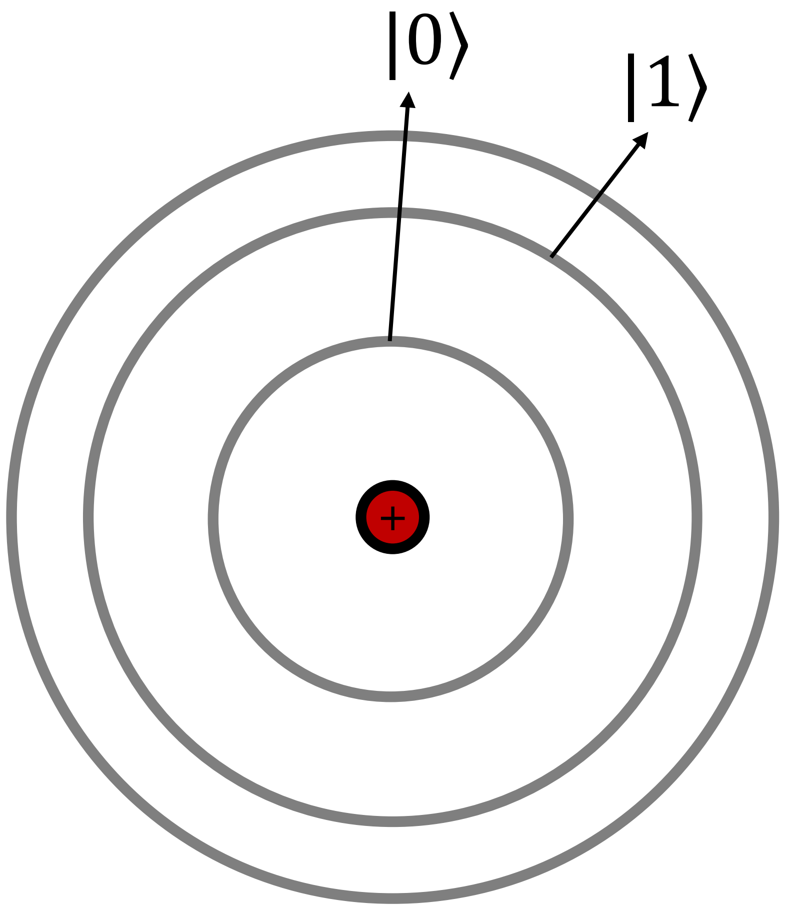






양자 시뮬레이션, 해밀토니안 시뮬레이션

Qubit



원자 에너지 레벨

비트: 고전 상태 0과 1로 이루어진 정보 단위
<u>큐비트: 양자 상태 $|0\rangle$과 $|1\rangle$로 이루어진 정보 단위</u>

- 원자나 이온의 두 에너지 레벨
- 초전도체의 두 에너지 레벨
- 아무 양자 시스템의 두 에너지 레벨 (광자, 양자점, NV 센터, ...)

2-레벨 시스템의 양자 상태(=큐비트):

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$\alpha \neq 0,\ \beta \neq 0$이면 "중첩"상태

Bloch sphere

Pasqal

2-레벨 시스템의 양자 상태(=큐비트):

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

양자역학에서,

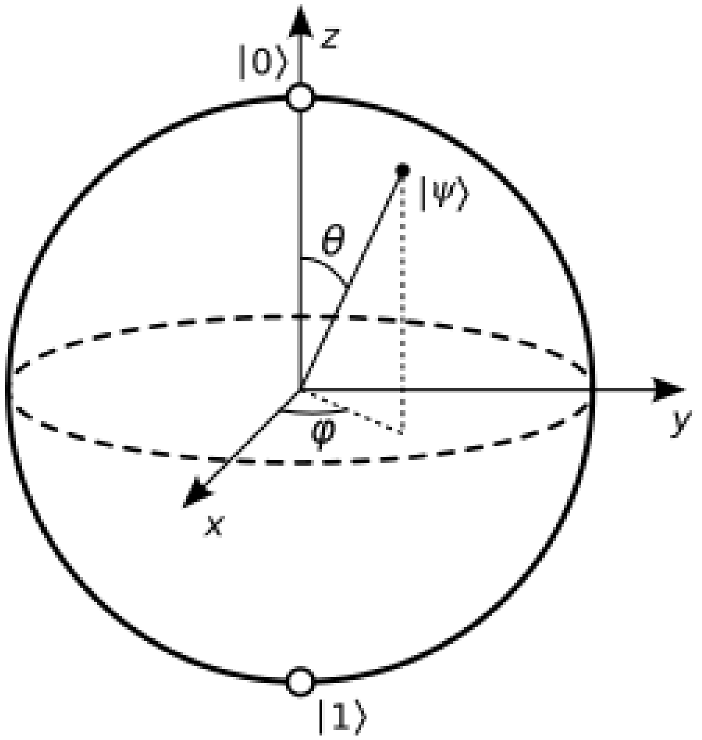
- 양자 상태의 coefficient인 α와 β는 복소수
- 측정 시 $|0\rangle$과 $|1\rangle$이 나올 확률은 각각 $|\alpha|^2$, $|\beta|^2$
- 따라서 $|\alpha|^2$과 $|\beta|^2$는 0과 1 사이, $|\alpha|^2 + |\beta|^2 = 1$ 이어야

이런 성질에 따라 큐비트를 아래와 같은 식으로 표현 가능

$$|\psi\rangle = \sin\frac{\theta}{2}\,|0\rangle + e^{i\phi}\cos\frac{\theta}{2}|1\rangle$$

(ϕ는 $|0\rangle$과 $|1\rangle$ 사이의 위상차)

또한, 이것을 오른쪽과 같이 “Bloch sphere”로 표현 가능



Bloch sphere representation of a qubit

Rabi oscillation

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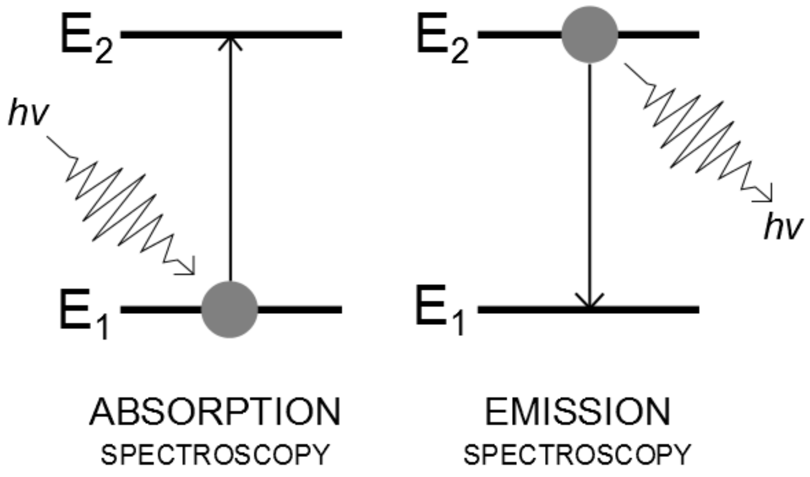
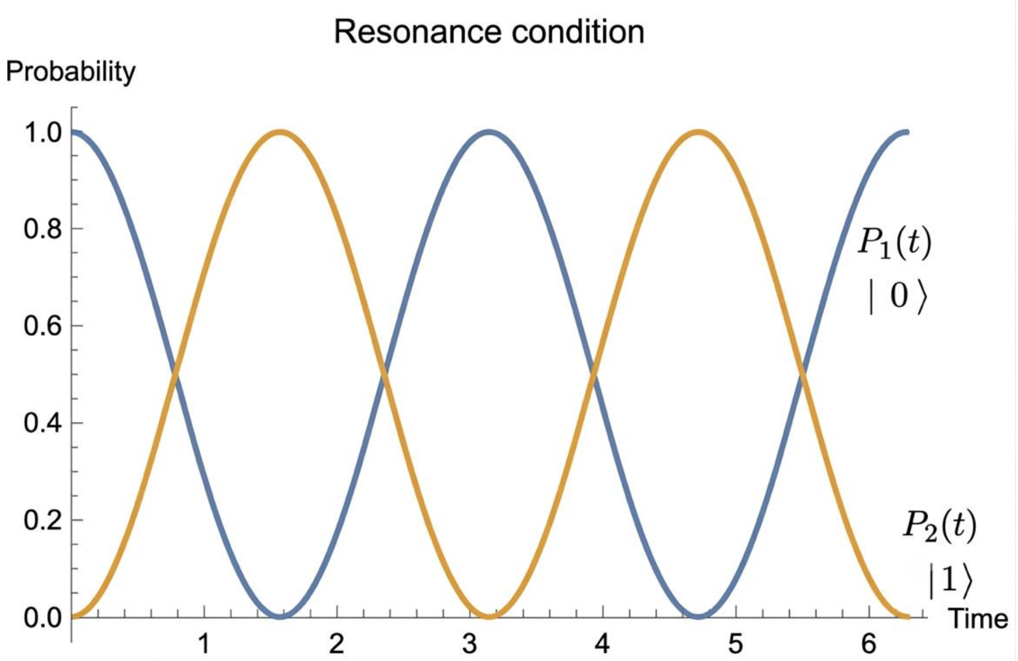
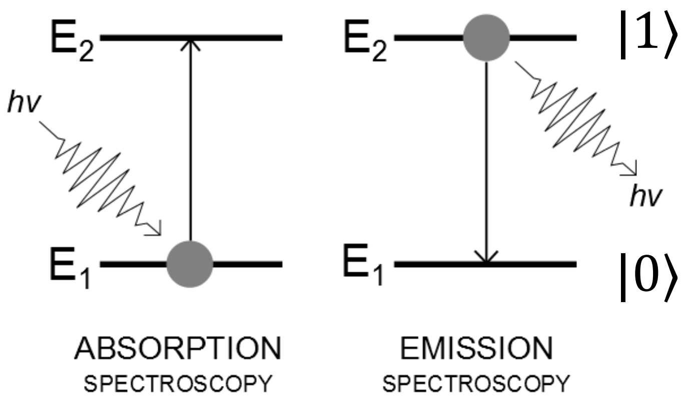
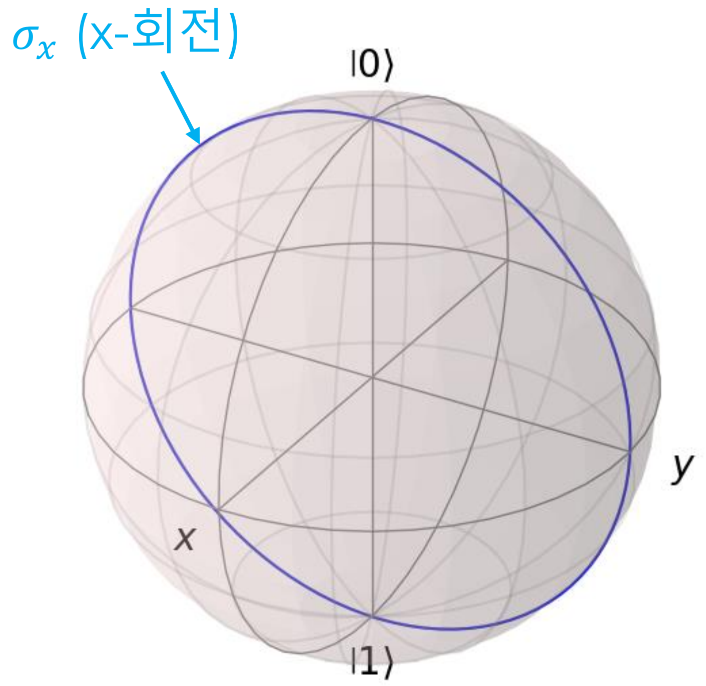


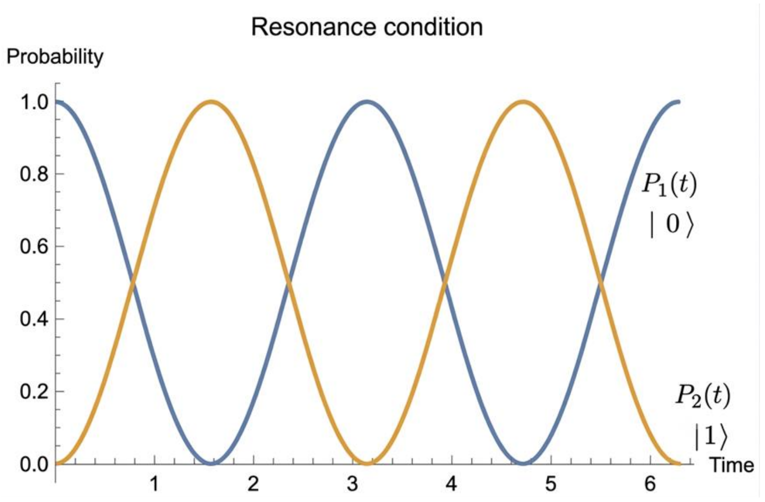


- 원자(또는 이온, 초전도체)의 어떤 2-레벨 시스템에 공진 주파수를 갖는 레이저 또는 마이크로파를 쏘면, 원자가 이 광자를 흡수하고 방출하면서 두 레벨 사이를 왔다갔다 함 ⇨ Rabi oscillation
- 이를 이용해서 1-큐비트 양자 게이트를 만들 수 있음 (고전 NOT 게이트 ⇨ 양자 X 게이트)

Rabi oscillation ⇨ X-회전







해밀토니안

$$H = \frac{\hbar\Omega}{2}\sigma_x$$

Ω: Rabi frequency 라비 주파수
(레이저 amplitude에 비례)

X-회전, Z-회전

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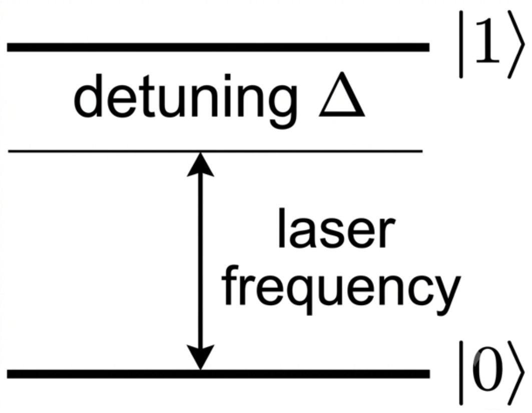
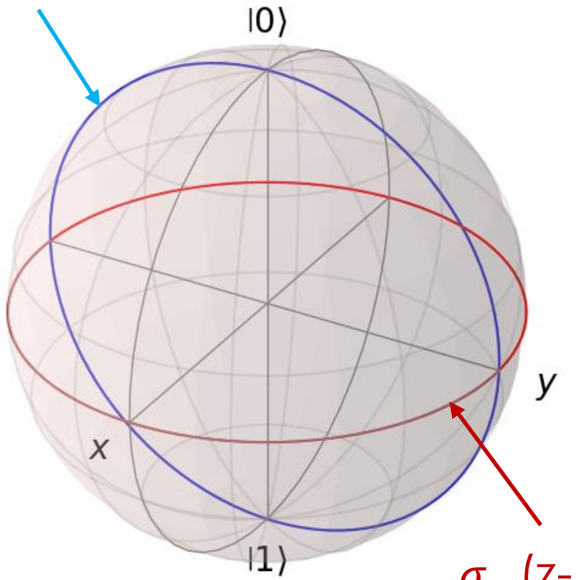
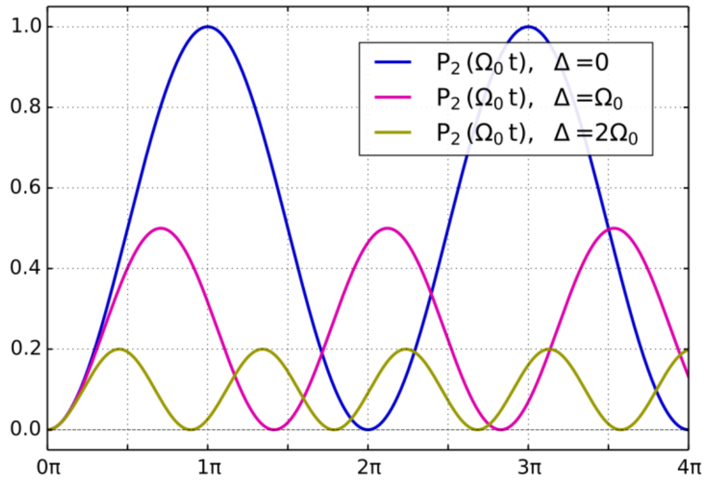


σ_x (x-회전) when $\Delta = 0$



σ_z (z-회전) when $\Delta \gg \Omega$



해밀토니안

$$H = \frac{\hbar\Omega}{2}\sigma_x + \frac{\hbar\Delta}{2}\sigma_z$$

Ω: Rabi frequency 라비 주파수 (레이저 amplitude에 비례)

Δ: Detuning 디튜닝 (레이저와 원자 레벨의 주파수 차이)

해밀토니안

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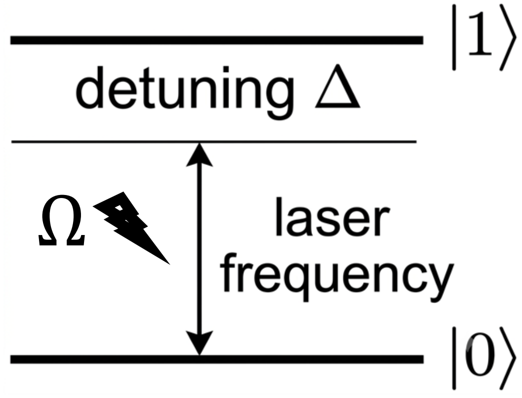
해밀토니안의 대각 성분은 각 상태의 에너지를 나타냄

$$H_0 = \begin{bmatrix} \mathrm{E}_0 & 0 \\ 0 & E_1 \end{bmatrix}$$



양자 상태의 시간 변화도 해밀토니안에 의해 정해짐 (슈뢰딩거 방정식)
e.g. Rabi oscillation의 해밀토니안

$$H_{\sigma_x} = \frac{\hbar\Omega}{2}\sigma_x = \hbar \begin{array}{cc} \begin{array}{cc} |0\rangle & |1\rangle \end{array} & \\ \begin{bmatrix} 0 & \Omega/2 \\ \Omega/2 & 0 \end{bmatrix} & \begin{array}{c} |0\rangle \\ |1\rangle \end{array} \end{array}$$

- 대각 성분들은 각 상태의 에너지. Atom-light 시스템에서 resonant한 레이저를 걸었을 때는 각각 0이 됨.
- 비대각 성분들은 두 상태 사이의 전이 세기를 나타냄. ⇨ 위의 경우 Rabi oscillation

$$H_{\sigma_z} = \frac{\hbar\Delta}{2}\sigma_z = \hbar \begin{bmatrix} \Delta & 0 \\ 0 & -\Delta \end{bmatrix}$$

*파울리 행렬:

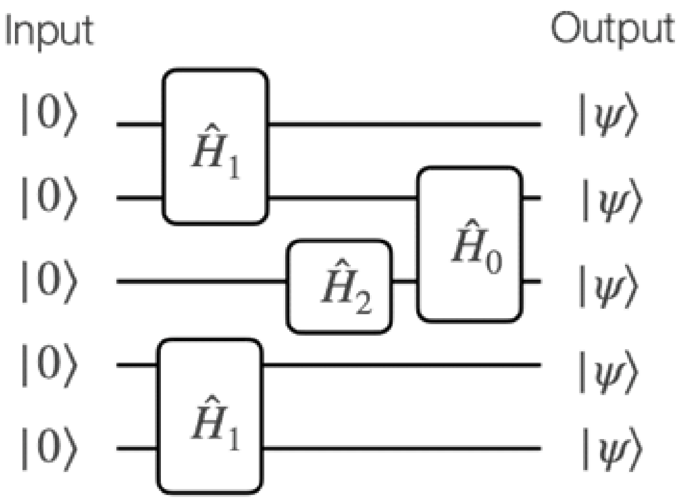
$$\sigma_1 = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix},$$
$$\sigma_2 = \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix},$$
$$\sigma_3 = \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

Analog or Digital Quantum Computing

Digital Control

Programming a quantum circuit with digital quantum gates

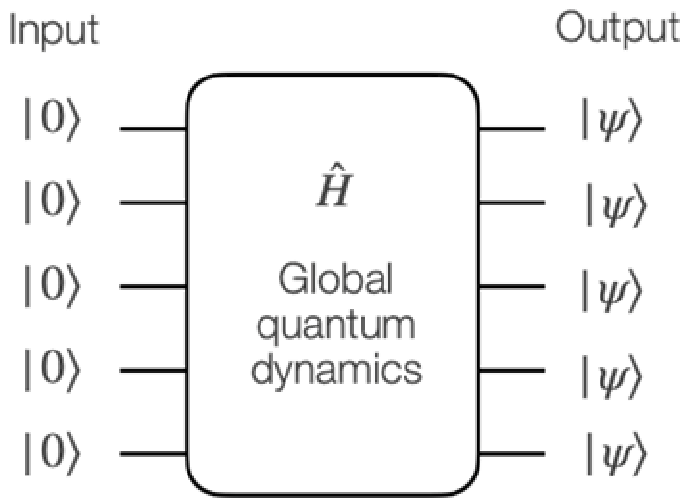
Elementary operations are discrete digital quantum gates, that can act either on individual qubits, or on several qubits at the same time.



Analog Control

Programming a Hamiltonian sequence

The Hamiltonian faithfully describes the dynamics of a physical quantum system or a reformulation of an operational case. Parameters can be tuned continuously.

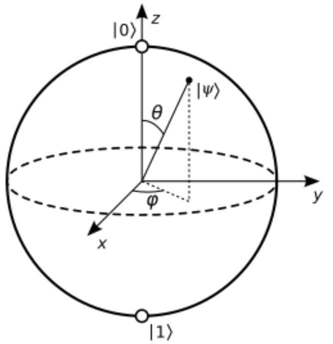


Digital quantum computing

Pasqal

1-qubit gates
(X, Y, Z, H, S, T, ... gate)

Laser frequency, intensity, phase, time, ..



e.g. Hadamard gate
(for basis change)

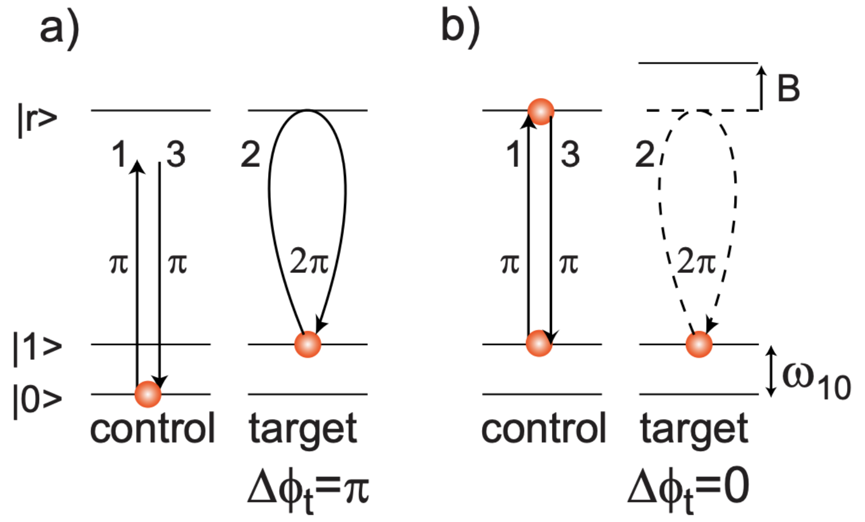
$$|0\rangle \leftrightarrow \frac{(|0\rangle + |1\rangle)}{\sqrt{2}}$$

$$|1\rangle \leftrightarrow \frac{(|0\rangle - |1\rangle)}{\sqrt{2}}$$

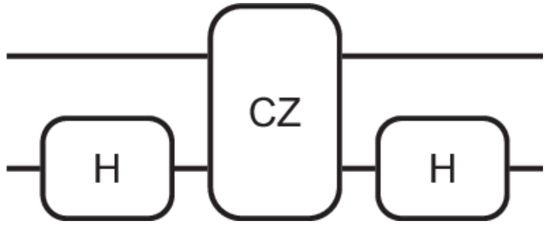
Operator	Gate(s)	Matrix
Pauli-X (X)	X, ⊕	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Pauli-Y (Y)	Y	$\begin{bmatrix}0 & -i\\i & 0\end{bmatrix}$
Pauli-Z (Z)	Z	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$
Hadamard (H)	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
Phase (S, P)	S	$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
$\pi/8$ (T)	T	$\begin{bmatrix}1 & 0\\0 & e^{i\pi/4}\end{bmatrix}$
Controlled Not (CNOT, CX)	⊕	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$
Controlled Z (CZ)	Z	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & -1\end{bmatrix}$

2-qubit gates
(C-NOT, CZ, entangling, ...)

Controlled-Z (CZ) gate with neutral atoms

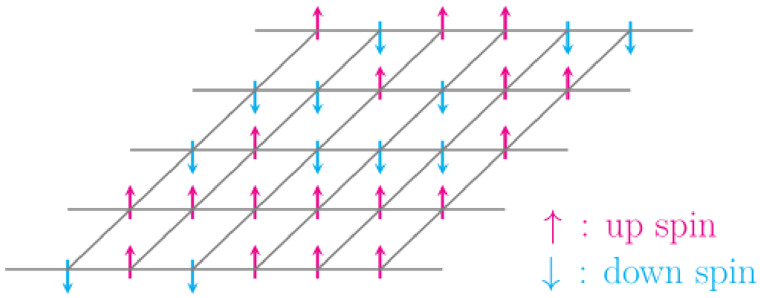


C-NOT gate



Analog quantum computing

Pasqal



e.g. Ising model /
Antiferromagnetic state

Transverse field

Ising couplings: $J_{ij} \propto 1/R_{ij}^6$

$$\mathcal{H}(t) = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_i^x - \hbar\delta(t)\hat{n}_i + \sum_{j<i} \frac{C_6}{(R_{ij})^6}\hat{n}_i\hat{n}_j \right)$$

$$\frac{1+\sigma_i^z}{2}$$

Quantum Simulation

Permits the simulation of quantum many-body systems far beyond the limits of classical computers, allowing, for example, the:

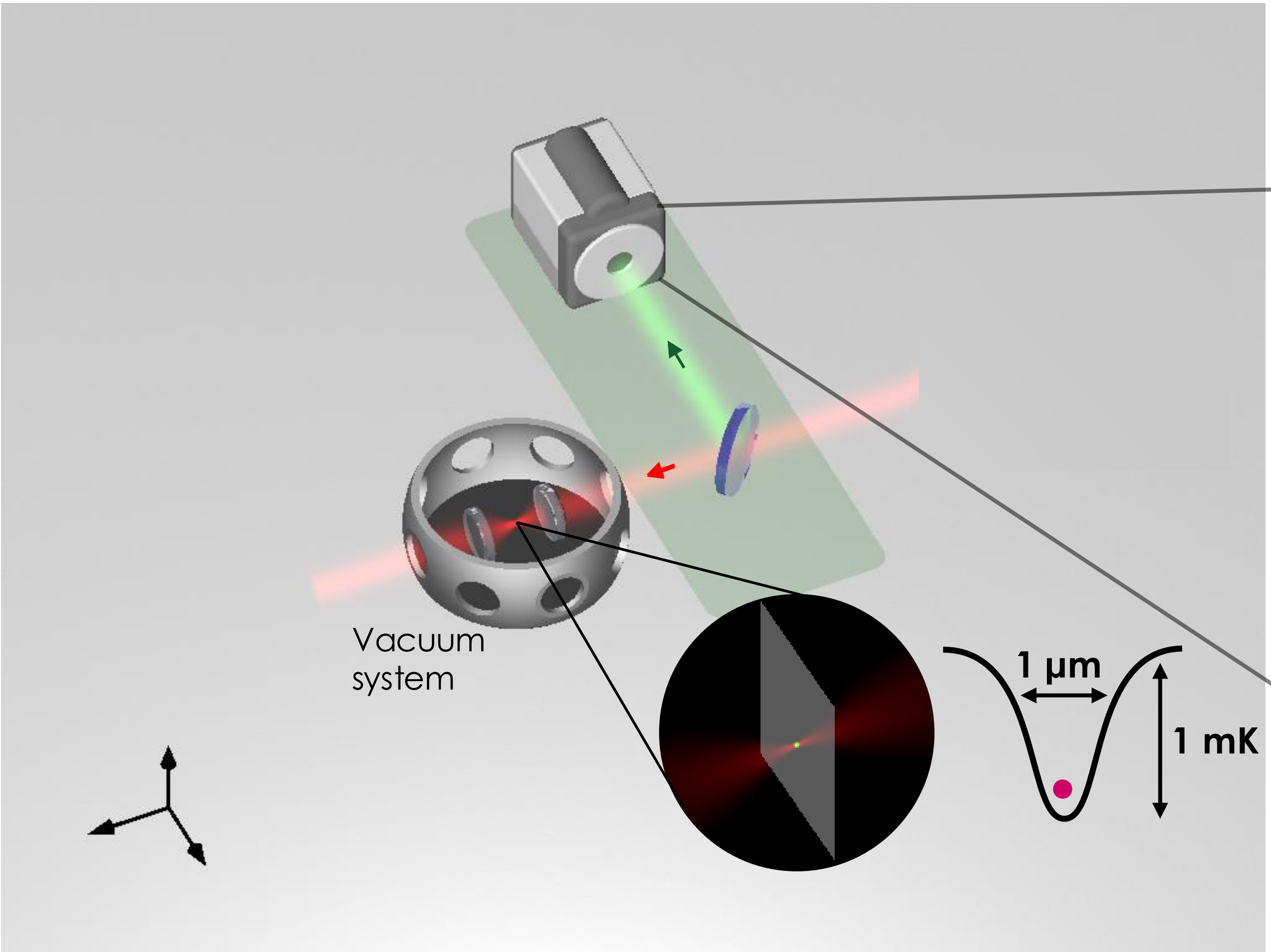
- Observation of out-of-equilibrium dynamics
- Adiabatic preparation of ground states

Pasqal Defining the quantum reality

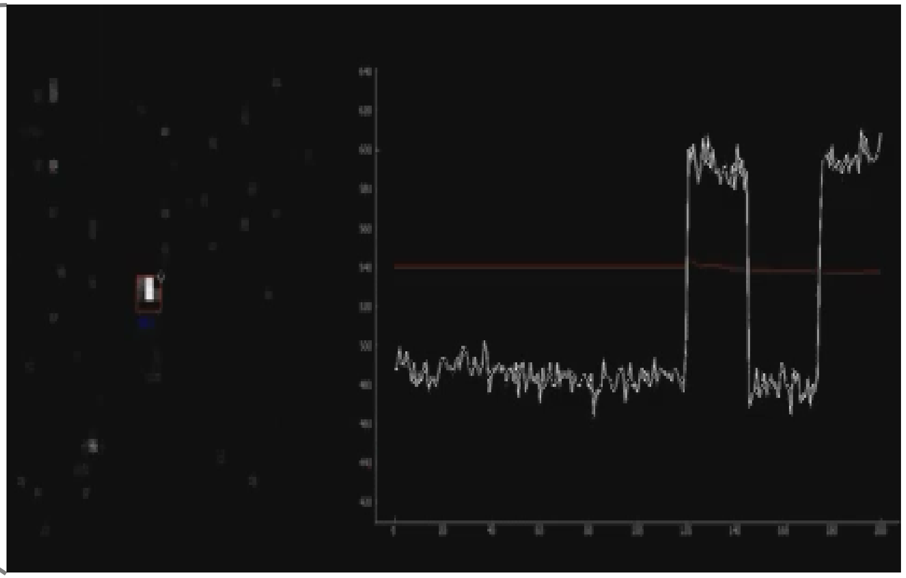
중성원자 양자컴퓨터

Creating the atomic array

Preparation of qubit register: three main steps



- Trapping of single atom into an optical tweezer [1]; no more than 1 atom per trap

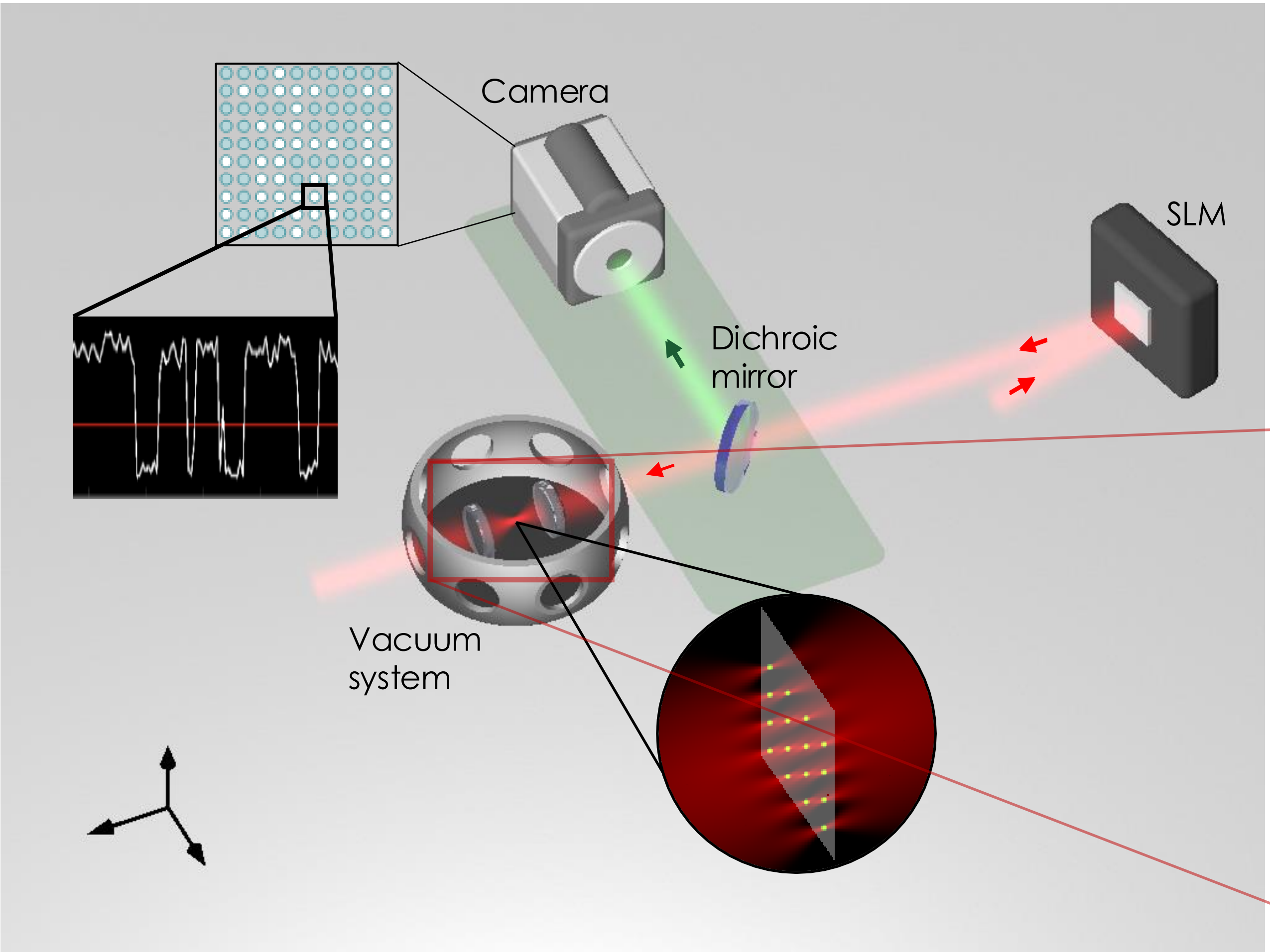


[1] N. Schlosser *et al.*, Nature **411**, 1024-1027 (2001)

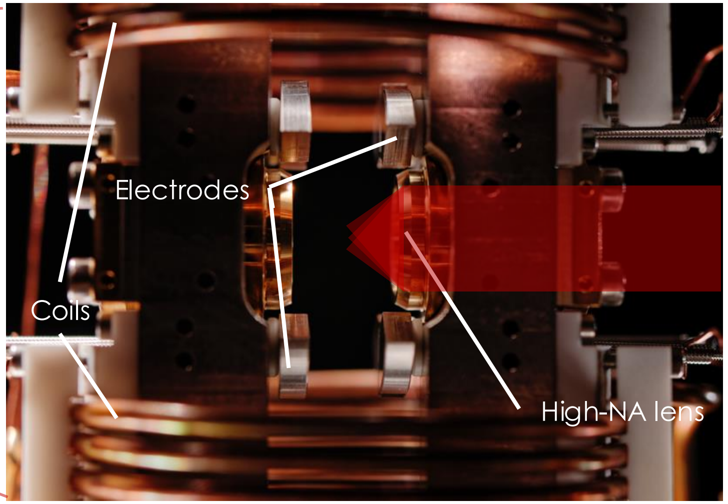
Creating the atomic array

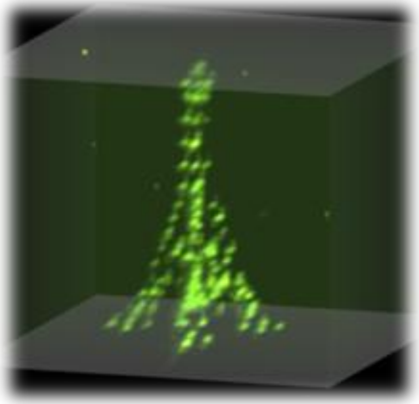
Preparation of qubit register: three main steps

Pasqal



- Trapping of single atom into an optical tweezer [1]; no more than 1 atom per trap
- Generation of optical tweezer arrays (1D – 2D; arbitrary) using SLM [2]



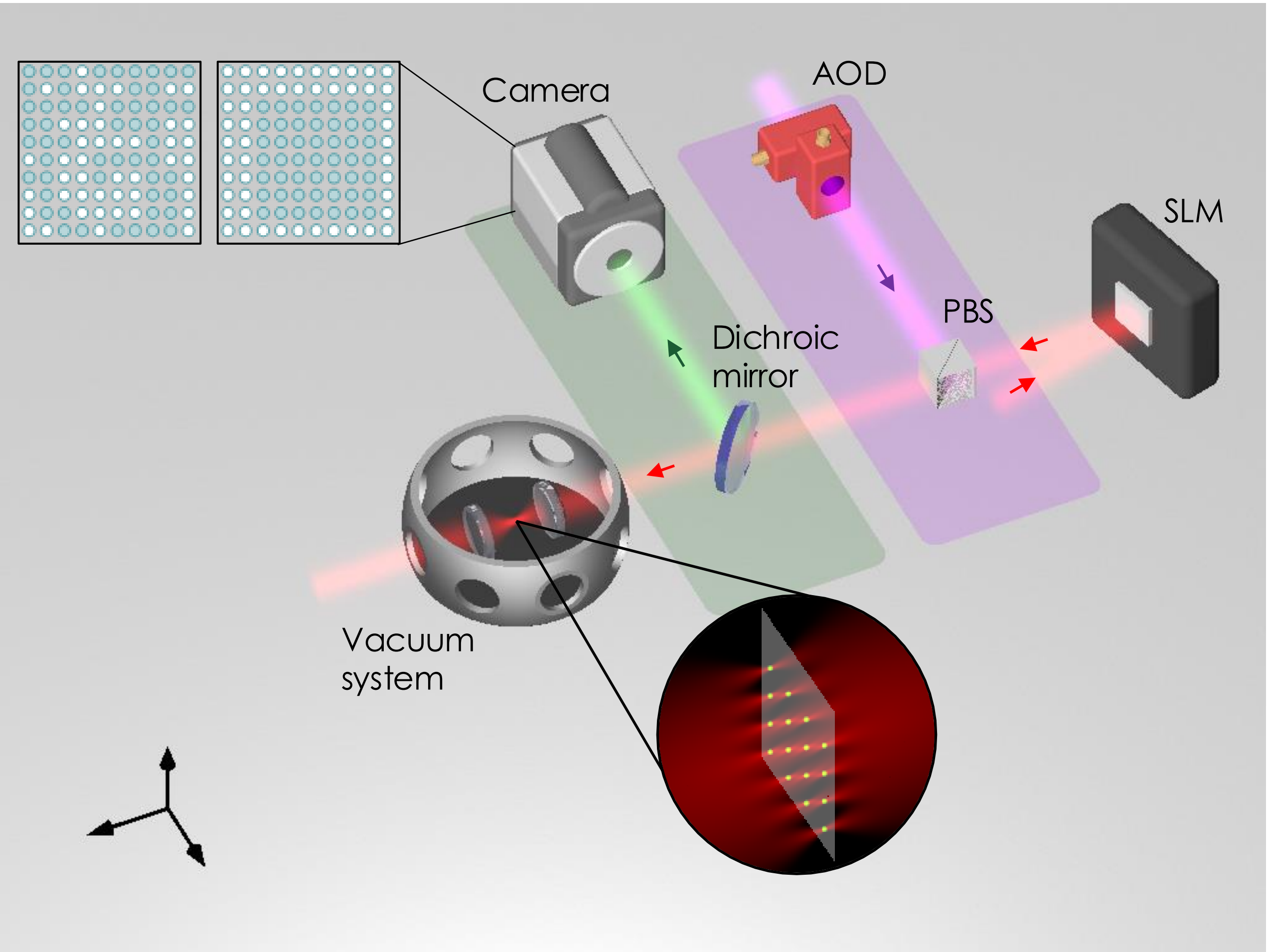


[1] N. Schlosser *et al.*, Nature **411**, 1024-1027 (2001)
[2] F. Nogrette *et al.*, Phys. Rev. X **4**, 021034 (2014)

Creating the atomic array

Pasqal

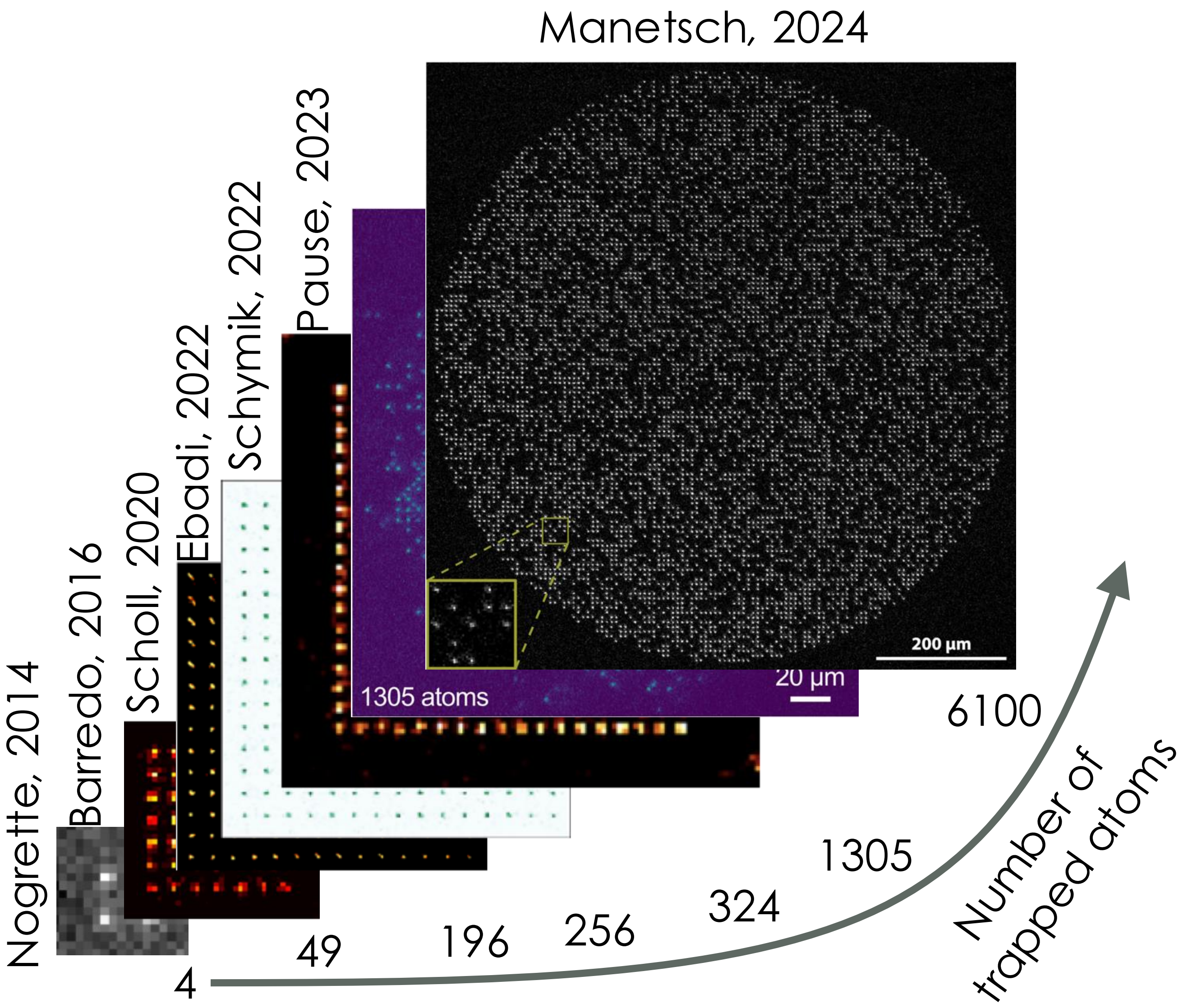
Preparation of qubit register: three main steps

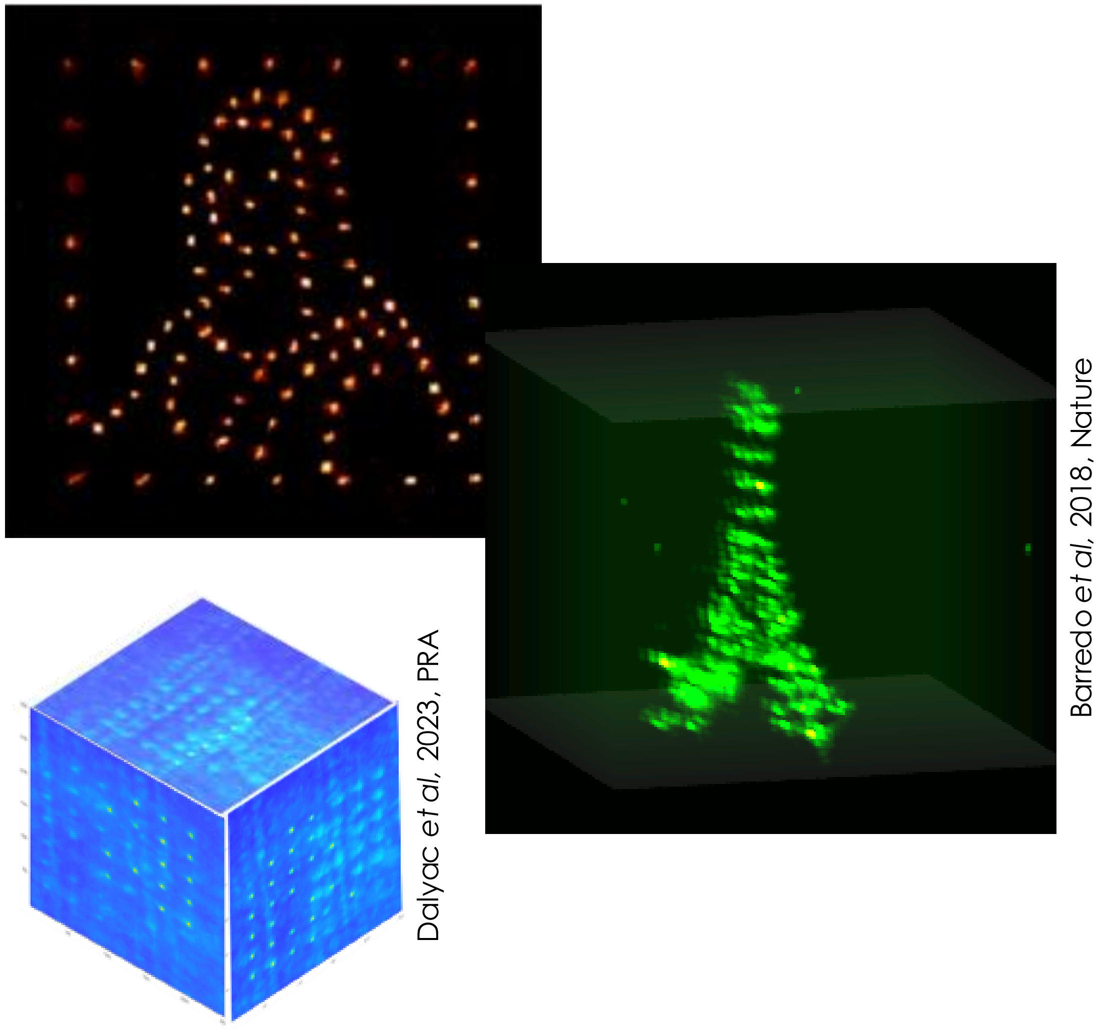


- Trapping of single atom into an optical tweezer [1]; no more than 1 atom per trap
- Generation of optical tweezer arrays (1D – 2D; arbitrary) using SLM [2]
- Reordering for **deterministic preparation** [3-4]

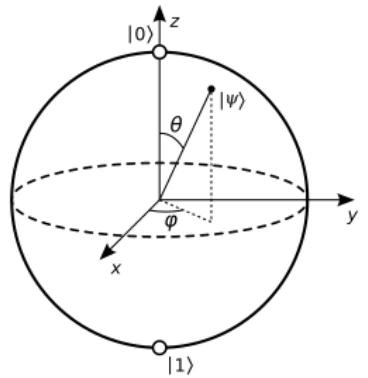
[1] N. Schlosser *et al.*, Nature **411**, 1024-1027 (2001)
[2] F. Nogrette *et al.*, Phys. Rev. X **4**, 021034 (2014)
[3] D. Barredo *et al.*, Science **354**, 1021-1023 (2016)
[4] M. Endres *et al.*, Science **354**, 1024-1027 (2016)

Scalability and arbitrary configuration

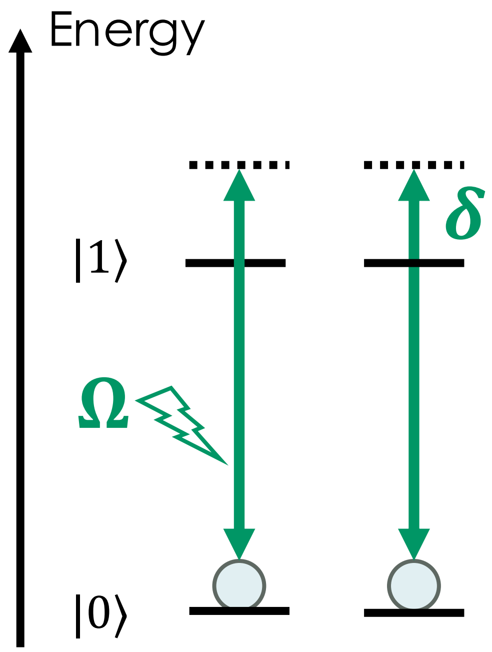




Hamiltonian and time evolution



Neutral atom system Hamiltonian



$$\hat{\mathcal{H}} = \hbar \sum_{i=1}^{N} \left(\frac{\Omega}{2} \hat{\sigma}_i^x - \delta\, \hat{n}_i \right) + \sum_{i<j} \frac{C_6}{|\mathbf{r}_i - \mathbf{r}_j|^6} \hat{n}_i \hat{n}_j$$

X-rotation Z-rotation Interaction

Ω: Rabi frequency (~ laser amplitude)

δ: Detuning (~ laser frequency offset)

$\hat{n}_i$: 0=ground, 1=excited

Hamiltonian and time evolution

Pasqal

$$\hat{\mathcal{H}} = \hbar \sum_{i=1}^{N} \left(\frac{\Omega}{2} \hat{\sigma}_i^x - \delta\, \hat{n}_i \right) + \sum_{i<j} \frac{C_6}{|\mathbf{r}_i - \mathbf{r}_j|^6} \hat{n}_i \hat{n}_j$$

Time evolution with H
(integral of Schrödinger eq.)

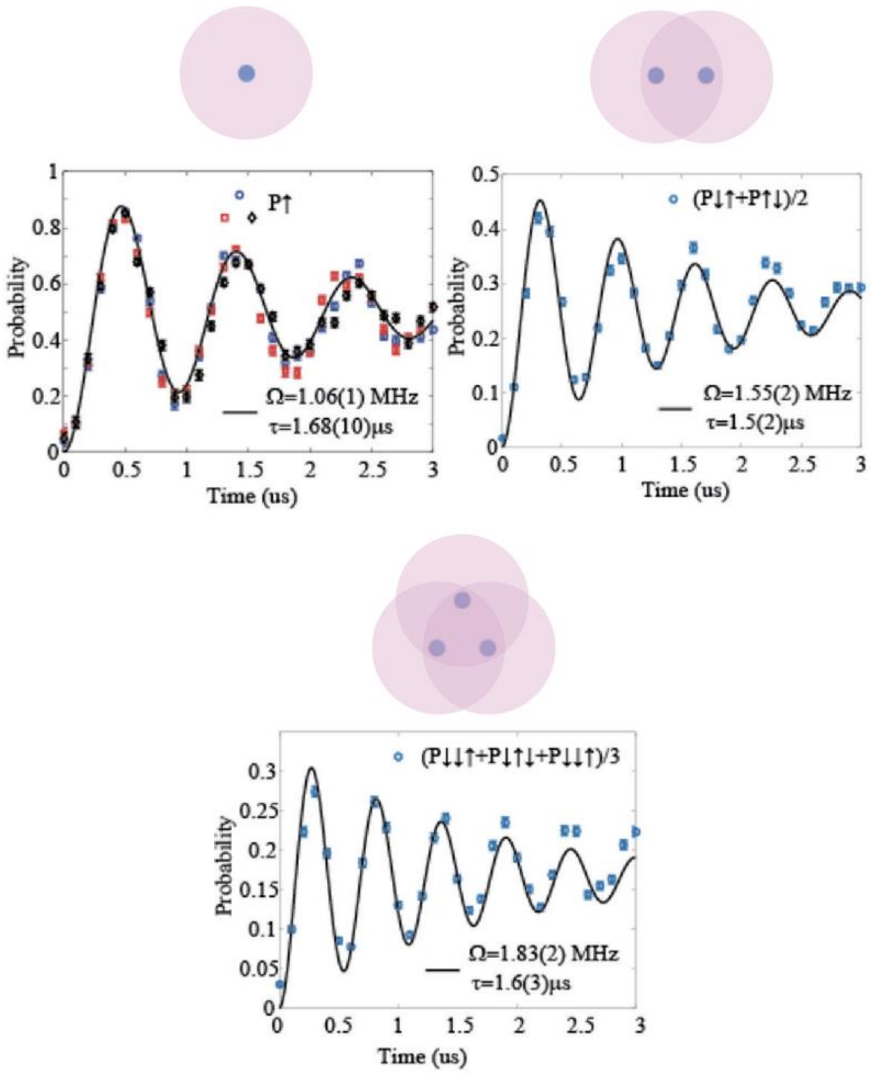
$$U(t) = \mathcal{T}\left[\exp\left(-\frac{i}{\hbar}\int_0^t H(t')dt'\right)\right]$$

Final state after time evolution

$$|\psi_f(t)\rangle = U(t)|\psi_0\rangle$$

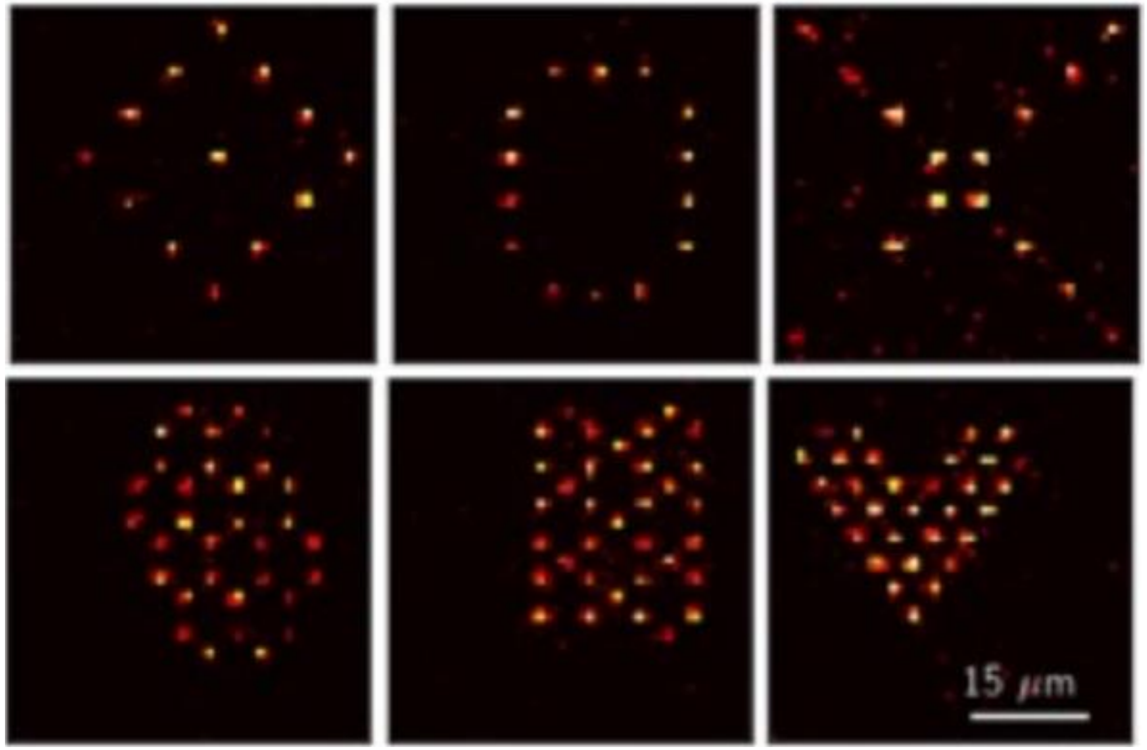
Example: $|\psi_0\rangle = \begin{bmatrix}1\\0\end{bmatrix}$ $\quad U = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$

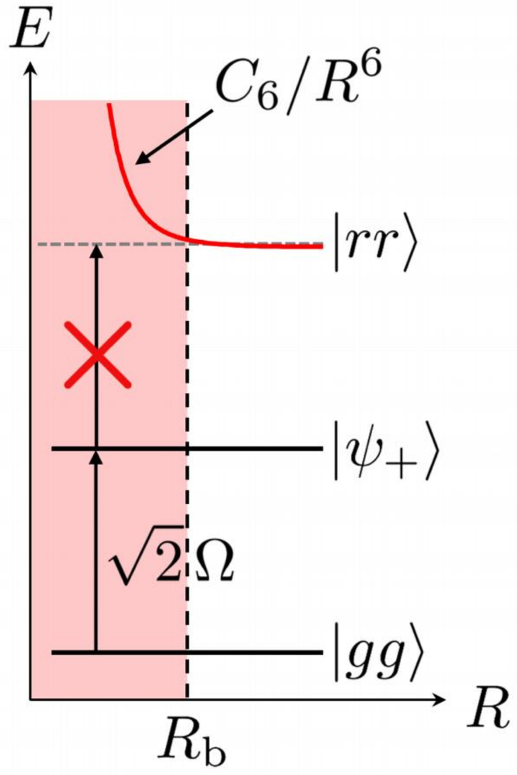
$|\psi_f\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$ (Hadamard gate)

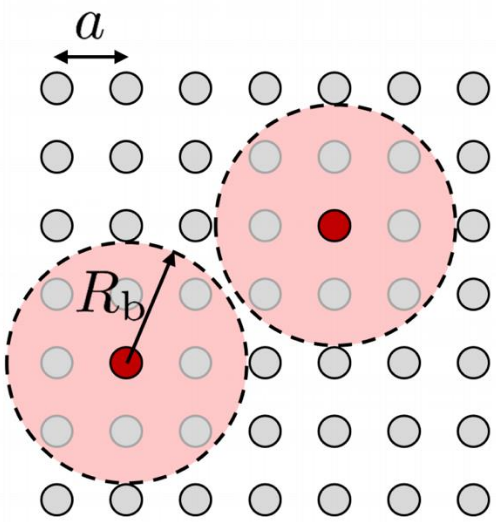


Rabi oscillation of Rydberg atoms

Quantum processing with more atoms





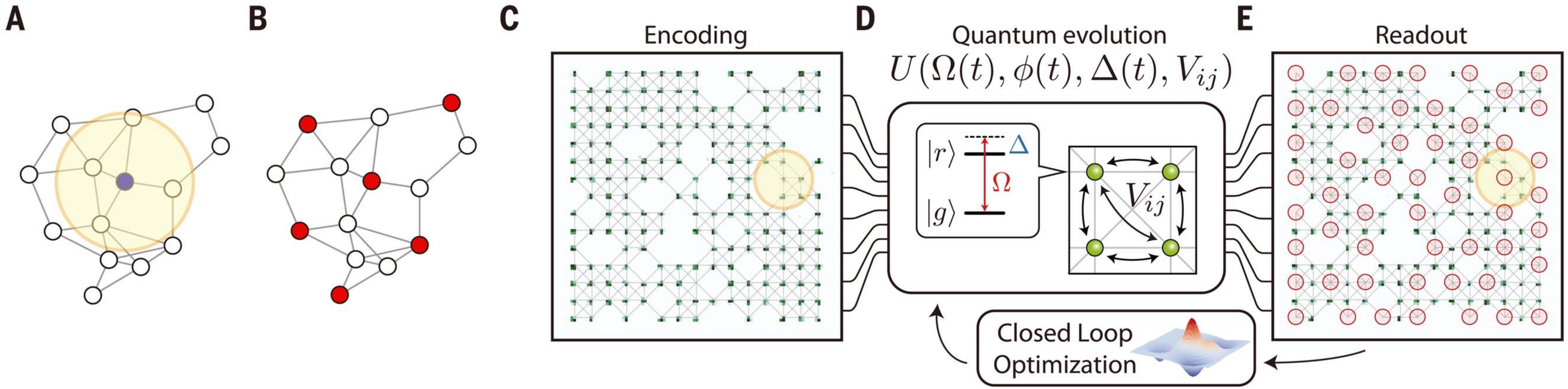


Maximum independent set (MIS) problem

Maximal independent set: subset of a graph with **no neighboring nodes**

Maximum independent set: **maximal indep. set with most number of nodes**

An NP-hard combinatorial optimization problem



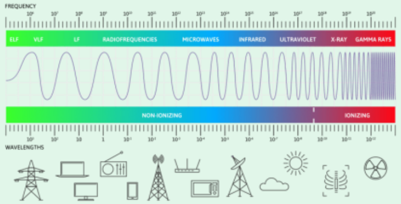
S. Ebadi et al. (2022)

Neutral atom use cases

Telecom

Antenna Placement

Frequency Assignment



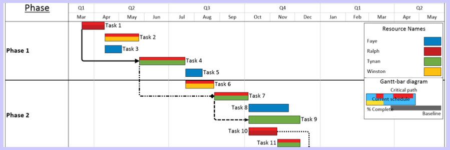
Energy

Transmission Expansion Planning

Sensor Placement for Power Grid Monitoring

Logistics

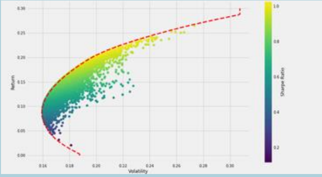
Project Task Scheduling with Conflicts



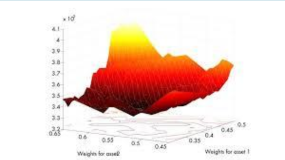
Truck/Vehicle Loading

Finance

Portfolio Optimization (Basic)



Portfolio Optimization (Realistic)



Pasqal Defining the quantum reality

Pasqal의 소프트웨어 스택

Software – an end-to-end stack to deliver solutions to users

Pasqal

Quantum Applications

Ready-to-use quantum algorithms, designed to address specific computational challenges

Quantum SDK

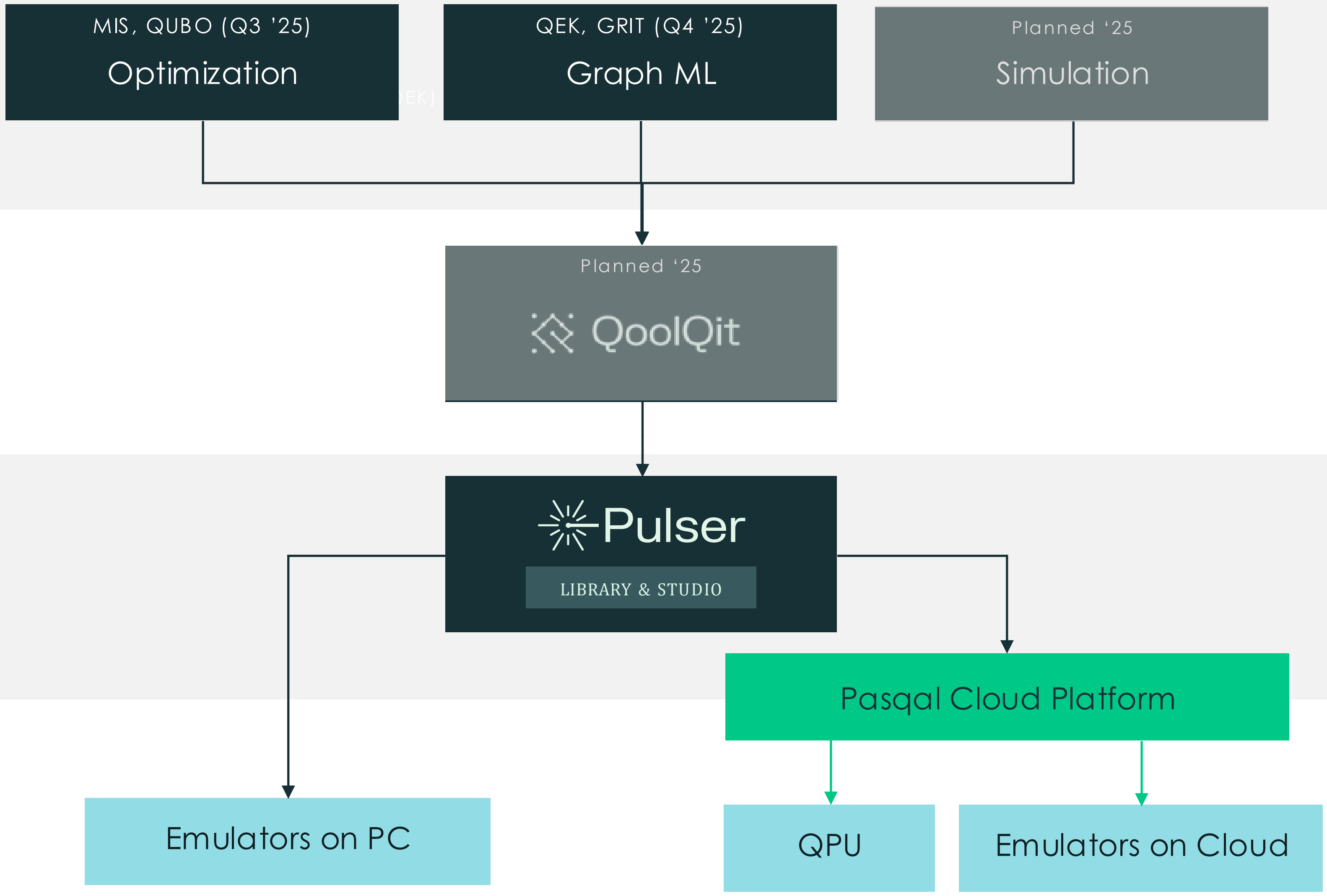
Create custom quantum applications with our intuitive, open-source SDK that simplifies algorithm development or use your favorite external SDK

Neutral Atom Programming

Pulser (and Pulser Studio) provide a flexible ecosystem for programming neutral atom quantum processors, supporting users of all skill levels

Execution

Access Pasqal QPUs and quantum emulators via our cloud platform, and run your jobs



Pasqal GitHub

Pasqal

github.com/pasqal-io

Popular repositories

Pulser Public

Library for pulse-level/analog control of neutral atom devices. Emulator with QuTiP.

Python 217 70

qadence Public

Digital-analog quantum programming interface

Python 89 21

quantum-evolution-kernel Public

A Graph Machine Learning library using Quantum Computing

Python 56 11

pyqtorch Public

PyTorch-based state vector and density matrix simulator

Python 48 27

horqrux Public

Jax-based quantum state vector simulator.

Python 26 3

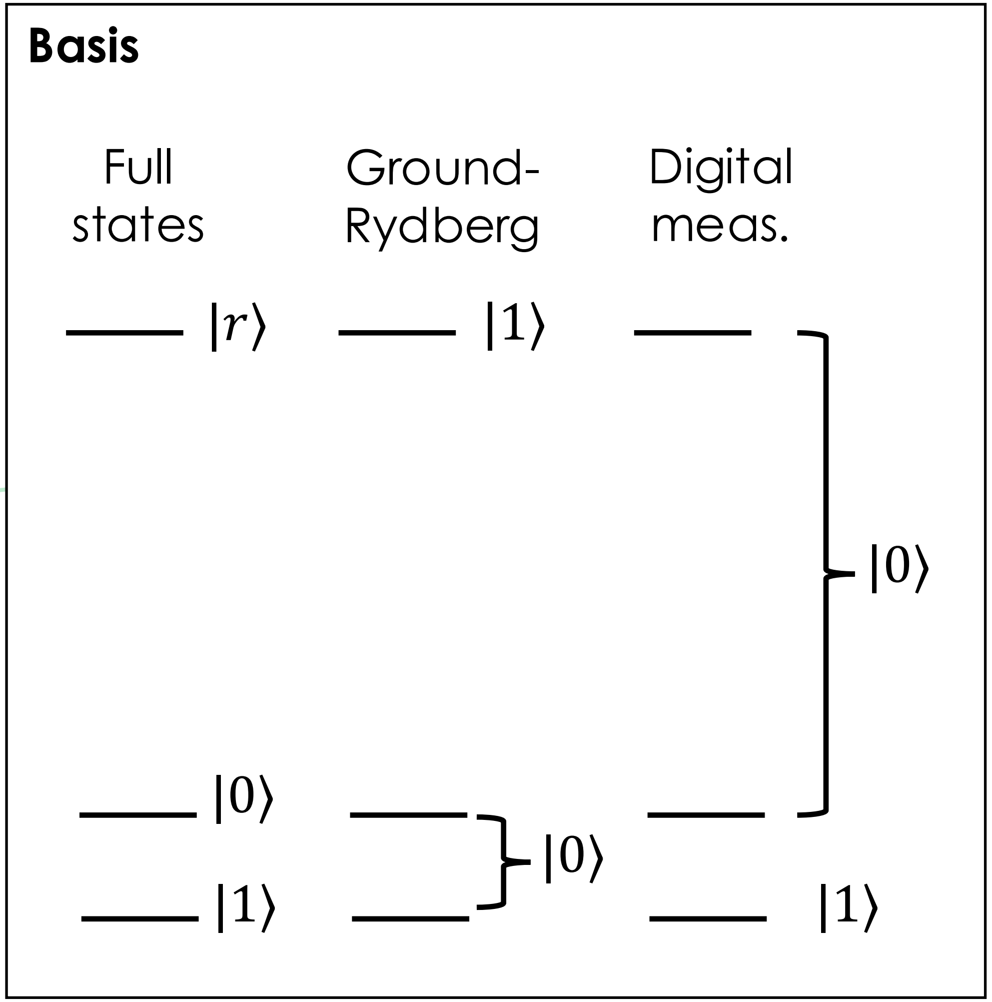
emulators Public

monorepo for pasqal torch based pulser backends

Python 21 3

Pulser Studio 실습

Pulser Studio



- **Antiferromagnetic states**
- **Maximum Independent Set**

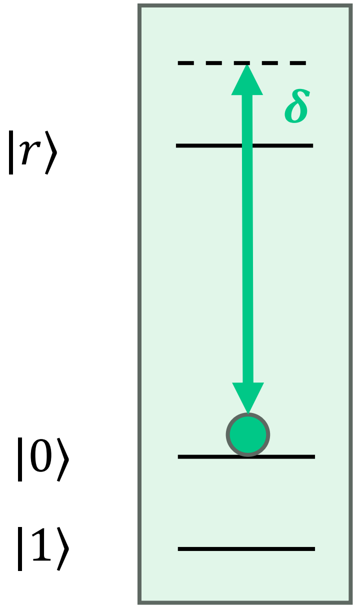
Pulser studio demonstration

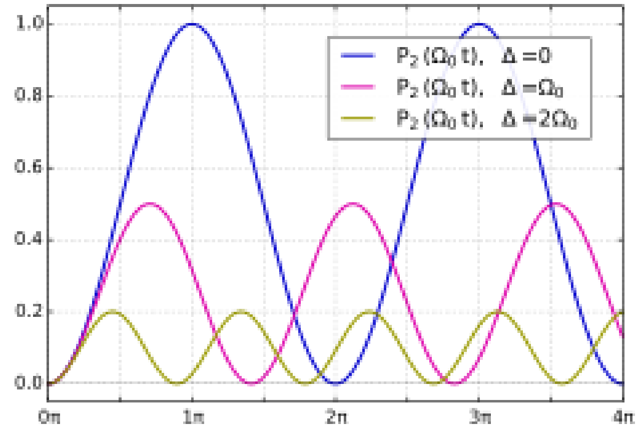
- 1-qubit gate
- Rydberg blockade → Entanglement
- C-Z gate
- Adiabatic quantum computing

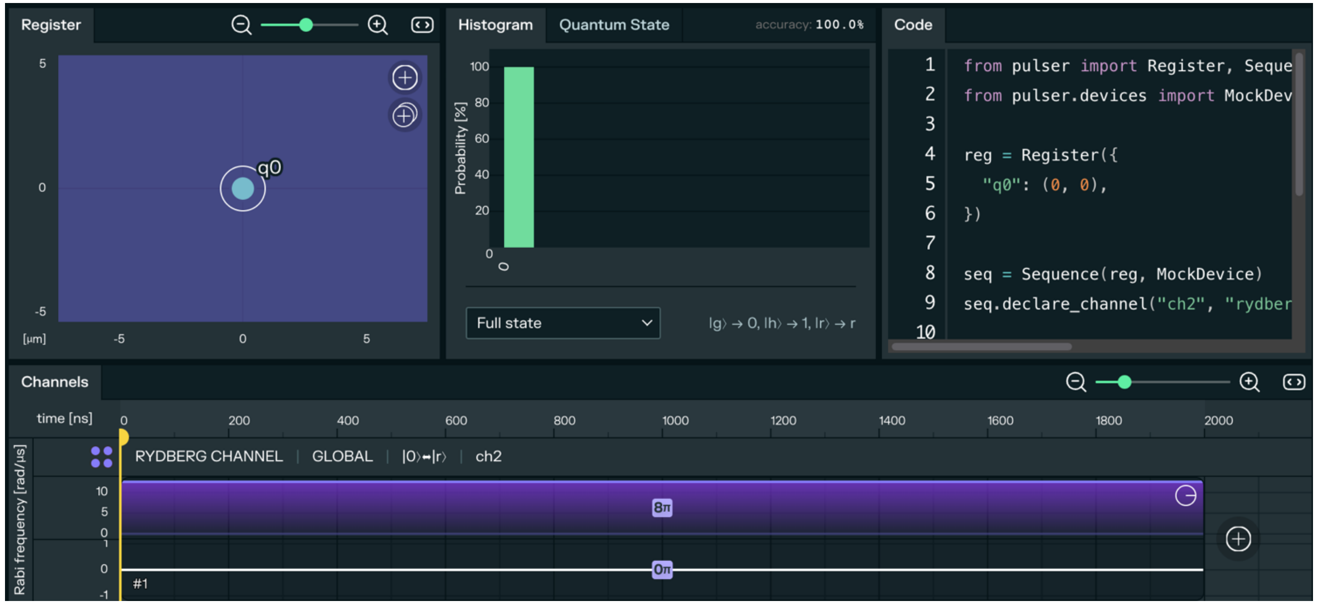
Pulser studio: 1-qubit gate (Rabi oscillation)

Pasqal

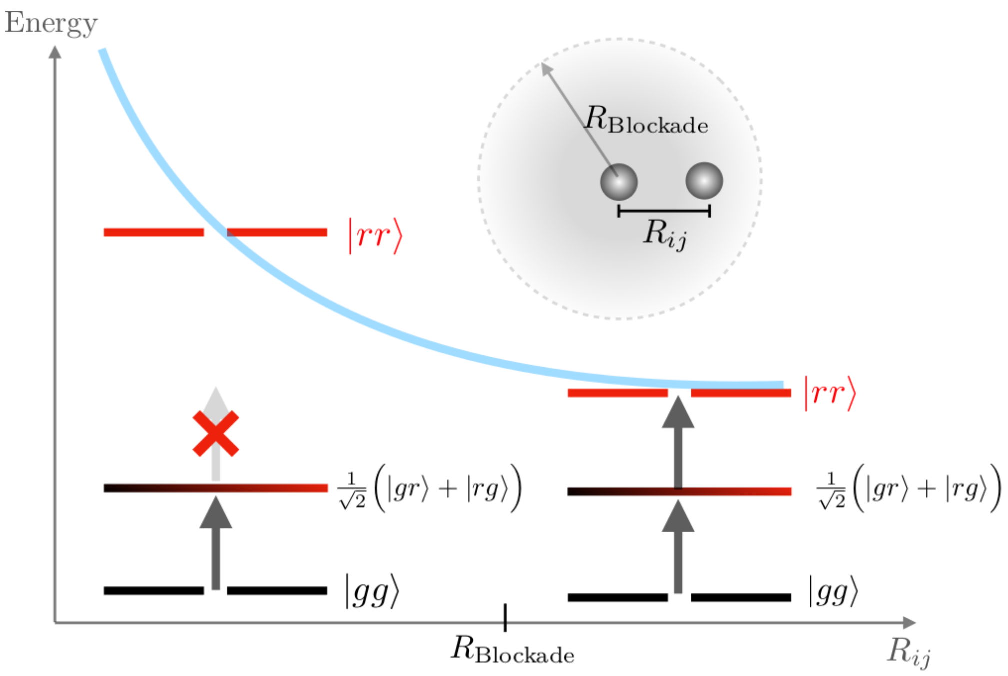
- Constant amplitude pulse
- Resonant (no-detuning): oscillates between $|0\rangle$ and $|1\rangle$
- Detuned: amplitude decreases

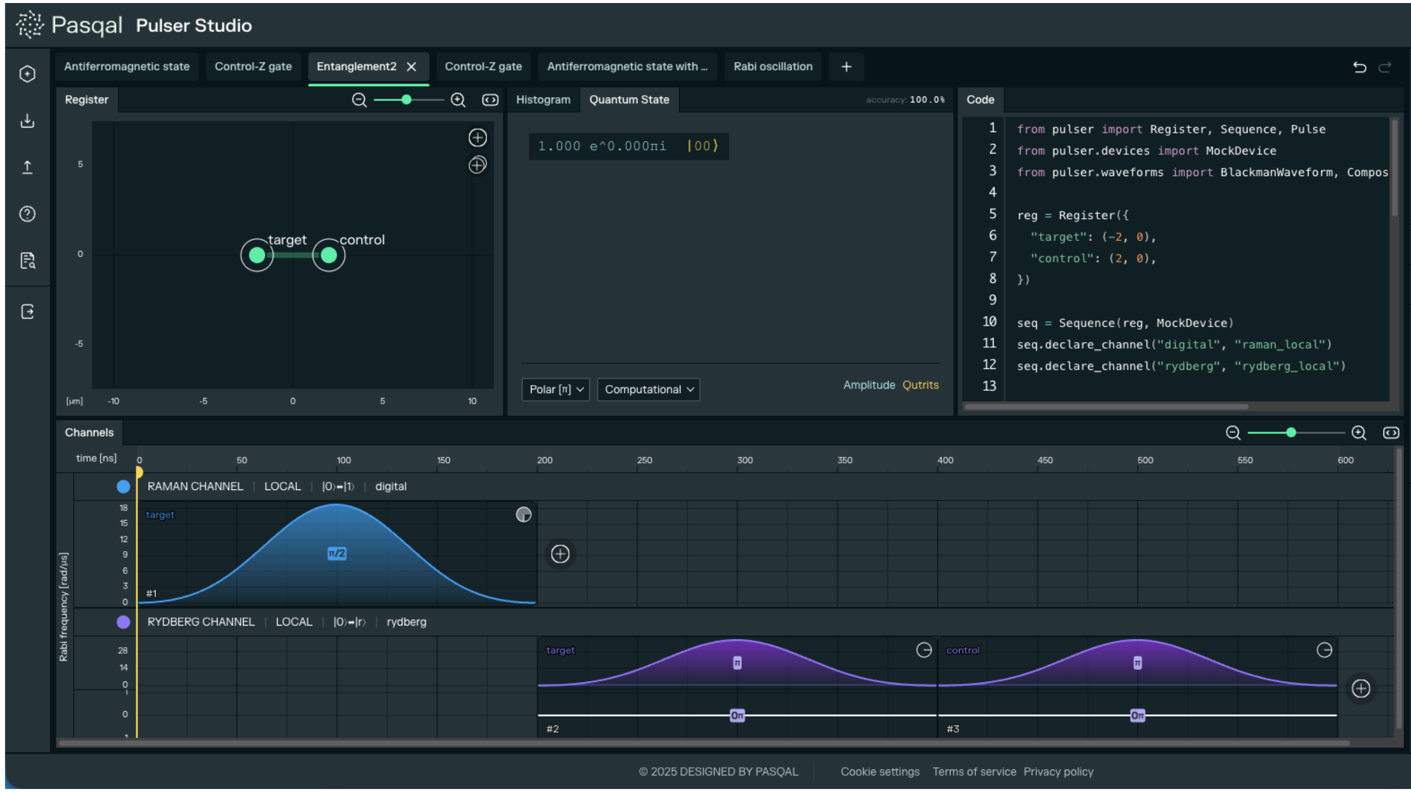






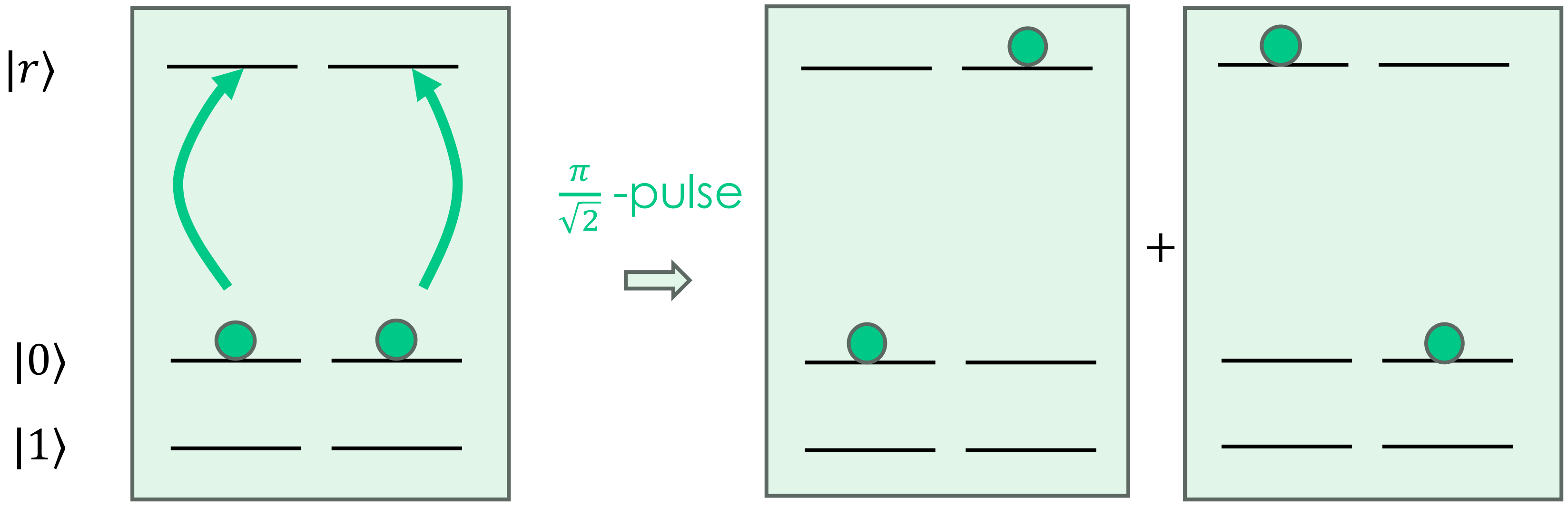
Pulser studio: Rydberg blockade





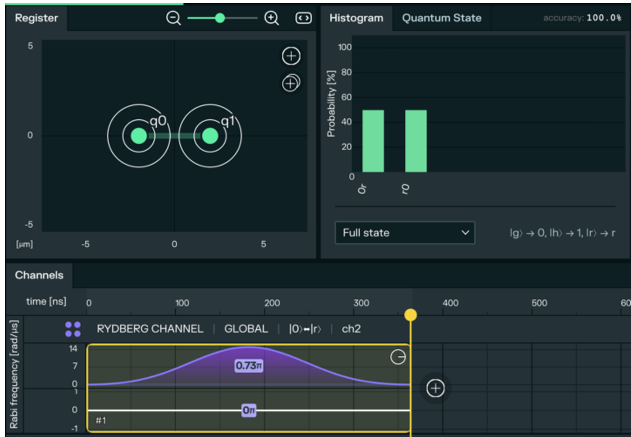
H. Silvério *et al.* (2022)

Pulser studio: Entanglement 1

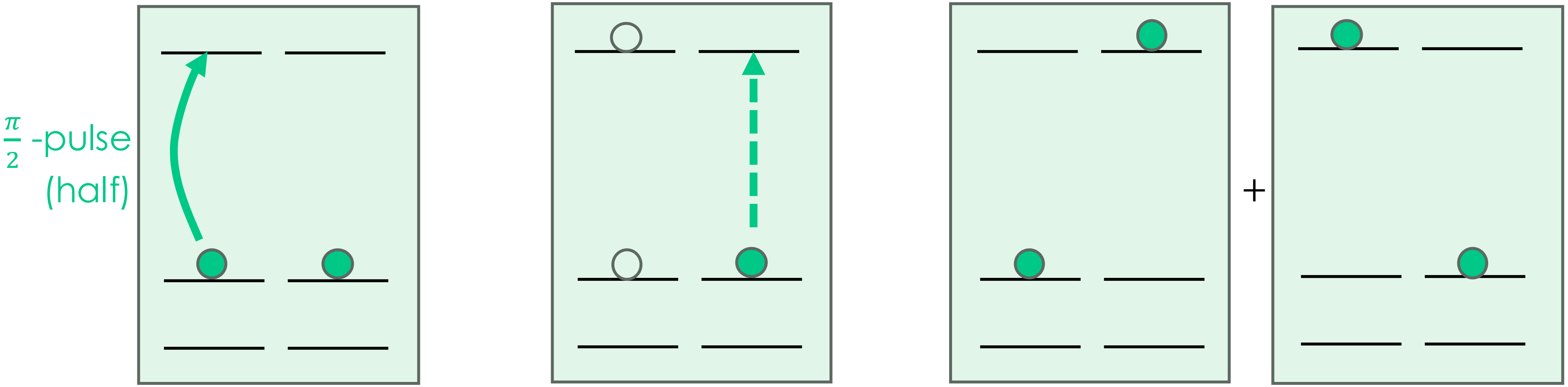


$|00\rangle$

$$\frac{|r0\rangle + |0r\rangle}{\sqrt{2}}$$

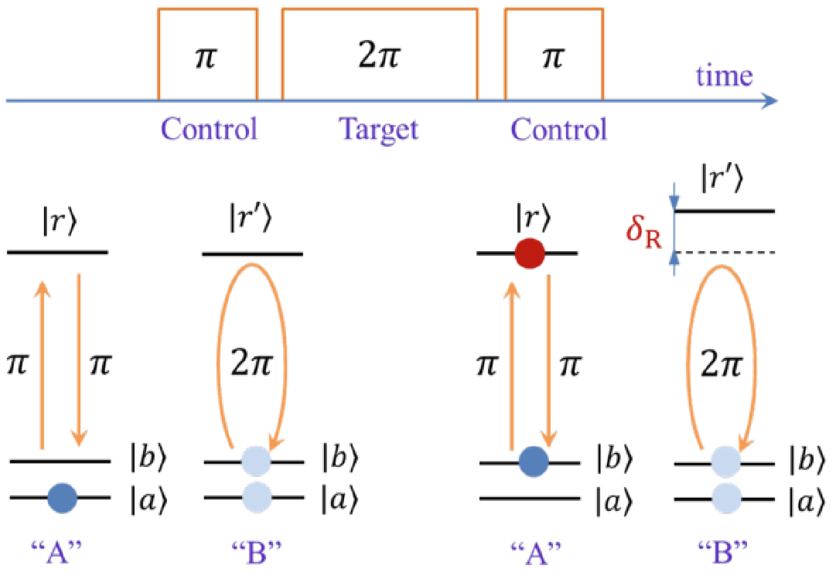


Pulser studio: Entanglement 2



$$|00\rangle \qquad \frac{|00\rangle + |r0\rangle}{\sqrt{2}} \qquad \frac{|0r\rangle + |r0\rangle}{\sqrt{2}}$$

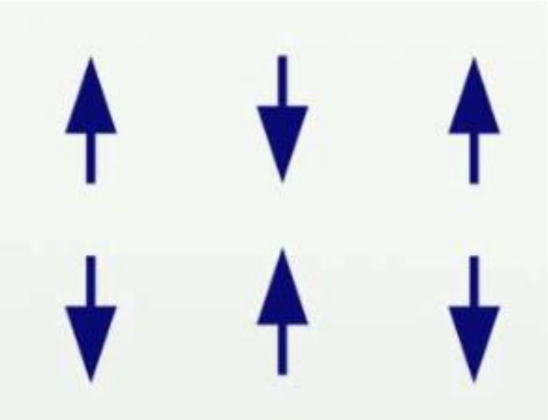
Pulser studio: Controlled-Z gate



L. Gerasimov, *Physical Review A*, *106*, 042410.
M. Saffman, *Reviews of modern physics*, *82*, 2313.

Pulser studio: Antiferromagetic state

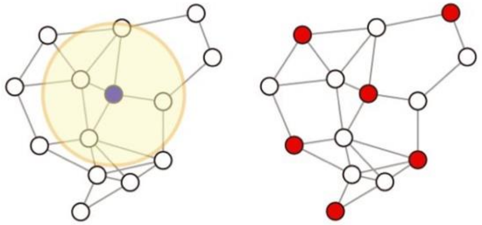
Pasqal



Pulser studio: Adiabatic quantum computing

Pasqal

Maximum Independent Set (MIS) problem



https://medium.com/the-modern-scientist/max-independent-set-battle-royal-296bf197e61b

Any questions?

Pasqal

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Technical Business Developer
woojun.lee@pasqal.com