# Laboratorio di computazione quantistica


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Quantum Research - CERN

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QUANTUM
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# Programma

- Lezione 1: Qiskit introduction
- Lezione 2: Quantum Algos and Noise
- Lezione 3: QC for Physics and QML
- Lezione 4: group project introduction
- Workshop: it’s your turn

# Agenda – Lezione 1

- Introduction IBM Q Lab
- Simple Exercise on Quantum Mechanics
- Homework

# Problems for a quantum computer

Modeling nature at the quantum level

Mathematics

Quantum chemistry,
Material science and
High energy physics

Algebraic algorithms
with provable speed-ups

- Shor’s Algorithm
- Grover’s Algorithm

Empirical heuristic
algorithms

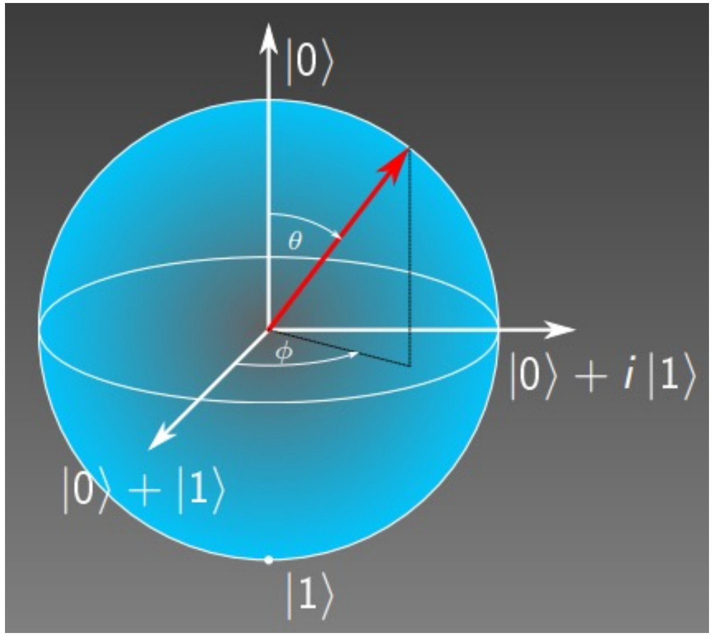
- Optimization
- Machine learning

# Basics of the circuit model of quantum computing

*Quantum bits*

- Qubit: two-dimensional quantum system
- Hilbert space H with basis {|0>, |1>}
- Contrary to classical bits, it can be in a superposition

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




$$\vec{r} = \begin{pmatrix} \sin(\theta)\cos(\phi) \\ \sin(\theta)\sin(\phi) \\ \cos(\theta) \end{pmatrix}$$

# Basics of the circuit model of quantum computing

- *n qubits*: Hilbert space is the tensor product

$$\underbrace{\mathcal{H} \otimes \cdots \otimes \mathcal{H}}_{n \text{ times}}$$

- Most general state in the computational basis

$$|\psi\rangle = \sum_{i_1,\ldots,i_n=0}^{1} c_{i_1\ldots i_n} |i_1\rangle \otimes \cdots \otimes |i_N\rangle$$

- A quantum state that cannot be factored as a tensor product of states of its local constituents is called **entangled**

$$|\psi_1\rangle = \tfrac{1}{2}(|0\rangle \otimes |0\rangle + |0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle)$$
$$= \tfrac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes \tfrac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$\Rightarrow$ product state

$$|\psi_2\rangle = \tfrac{1}{\sqrt{2}}(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle)$$

$\Rightarrow$ entangled state (Bell state)

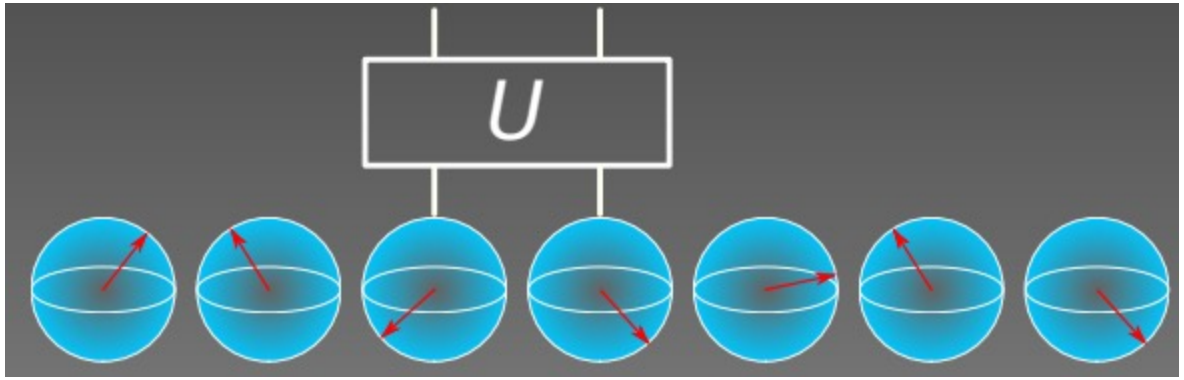
# Basics of the circuit model of quantum computin

## *Quantum gates*

- Quantum mechanics is reversible, |ψ> undergoes unitary evolution under some (time-dependent) Hamiltonian H(t)

$$|\psi(t)\rangle = T\exp\left(-i\int_0^t ds\, H(s)\right)|\psi_0\rangle$$

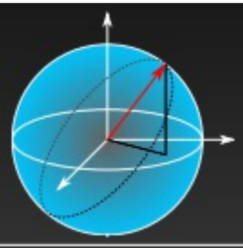
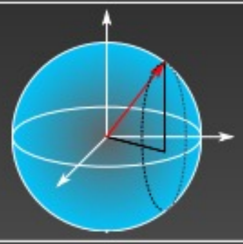
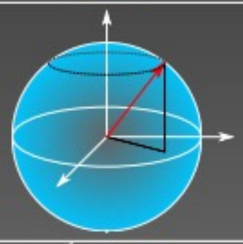
- Quantum gates are represented by unitary matrices
- Typically gates only act on a few qubits in a nontrivial way



# Common single-qubit quantum gates

| | | | |
|---|---|---|---|
| $X$ | $-\boxed{X}-$ | $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ | $\|0\rangle \rightarrow \|1\rangle$<br>$\|1\rangle \rightarrow \|0\rangle$ |
| $Y$ | $-\boxed{Y}-$ | $Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$ | $\|0\rangle \rightarrow -i\|1\rangle$<br>$\|1\rangle \rightarrow i\|0\rangle$ |
| $Z$ | $-\boxed{Z}-$ | $Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ | $\|0\rangle \rightarrow \|0\rangle$<br>$\|1\rangle \rightarrow -\|1\rangle$ |

# Common single-qubit quantum gates

| | | | |
|---|---|---|---|
| $R_x(\theta)$ | $-\boxed{R_x(\theta)}-$ | $R_x = \exp\left(-i\frac{\theta}{2}X\right)$ |  |
| $R_y(\theta)$ | $-\boxed{R_y(\theta)}-$ | $R_y = \exp\left(-i\frac{\theta}{2}Y\right)$ |  |
| $R_z(\theta)$ | $-\boxed{R_z(\theta)}-$ | $R_z(\theta) = \exp\left(-i\frac{\theta}{2}Z\right)$ |  |
| Hadamard | $-\boxed{H}-$ | $H = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$ | $\lvert 0\rangle \rightarrow \frac{1}{\sqrt{2}}(\lvert 0\rangle + \lvert 1\rangle)$ <br> $\lvert 1\rangle \rightarrow \frac{1}{\sqrt{2}}(\lvert 0\rangle - \lvert 1\rangle)$ |

# Common multi-qubits quantum gates

| | | | |
|---|---|---|---|
| CNOT |  | $\text{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$ | $\lvert 00\rangle \rightarrow \lvert 00\rangle$<br>$\lvert 01\rangle \rightarrow \lvert 01\rangle$<br>$\lvert 10\rangle \rightarrow \lvert 11\rangle$<br>$\lvert 11\rangle \rightarrow \lvert 10\rangle$ |
| $R_{xx}(\theta)$ | $-\boxed{R_{xx}(\theta)}-$ | $R_{xx}(\theta) = \exp\left(-i\frac{\theta}{2} X \otimes X\right)$ | |
| $R_{yy}(\theta)$ | $-\boxed{R_{yy}(\theta)}-$ | $R_{yy}(\theta) = \exp\left(-i\frac{\theta}{2} Y \otimes Y\right)$ | |
| $R_{zz}(\theta)$ | $-\boxed{R_{zz}(\theta)}-$ | $R_{zz}(\theta) = \exp\left(-i\frac{\theta}{2} Z \otimes Z\right)$ | |


# Thanks!

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