HDCRS Summer School
Introduction to Quantum Computing and its Ecosystem*

Mengoni Riccardo, PhD
1 June 2023

*with memes
CINECA Overview

• **CINECA** is a **Consortium** composed by 98 Italian universities and public institutions.

• Since its origins in 1969, Cineca offers **support to scientific research, public and industrial**, through **supercomputing and the use of the most innovative computing systems based on state-of-the-art architectures and technologies**.

• **HPC Italian National Center**, owner of one of the most powerful supercomputer in Europe and the World
Leonardo: Cineca pre-exascale supercomputer

Fourth most powerful supercomputers in the world

<table>
<thead>
<tr>
<th>Rank</th>
<th>System</th>
<th>Cores</th>
<th>Rmax (PFlop/s)</th>
<th>Rpeak (PFlop/s)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Leonardo - BullSequana XH2000, Xeon Platinum 8358 32C 2.6GHz, NVIDIA A100 SXM4 64 GB, Quad-rail NVIDIA HDR100 Infiniband, Atos EuroHPC/CINECA</td>
<td>1,824,768</td>
<td>238.70</td>
<td>304.47</td>
<td>7,404</td>
</tr>
</tbody>
</table>
Quantum Computing @ CINECA

CINECA: Italian HPC center
CINECA Quantum Computing Lab:
- Support research Universities, Industries and QC startups
- Internship programs, Courses and Conference (HPCQC)

https://www.quantumcomputinglab.cineca.it
What is Quantum Computing?
What is Quantum Computing?
What is Quantum Computing?

A Quantum Computer is **NOT** simply a smaller or faster version of traditional computers or HPC systems.
What is Quantum Computing?

A fundamentally new paradigm for information processing and computation

Based on the principles of Quantum Physics
What is Quantum Computing?

Quantum Algorithms ≠ Classical Algorithms

• A completely different approach is required to solve problems (because involves quantum mechanics)

YOU DON'T SIMPLY
PORT *APPLICATION* TO QPU
Let’s take a step back.. What is Quantum Mechanics?
What is Quantum Mechanics?

“If you remove all the physics
QM= probability theory + minus sign”

Cit. Scott Aaronson

https://www.youtube.com/watch?v=SczraSQE3MY
What is Quantum Mechanics?

"If you remove all the physics
QM = probability theory + minus sign"

Citr. Scott Aaronson

..also Linear algebra Involved

Vectors (ket)

$$|\psi\rangle = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_n \end{pmatrix} \quad \psi_i \in \mathbb{C}$$

Complex Number

Tensor Product

$$|\phi\rangle \otimes |\psi\rangle = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_n \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_n \end{pmatrix}$$

Dimension = $$n^2$$

Unitary Operators

$$UU^\dagger = U^\dagger U = I$$

Hermitian Operators

$$A = A^\dagger$$

Postulates of Quantum Computing

1. Unit of Information
Classically

Unit of classical information is the bit

State of a bit:

\[ |0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \]
To a closed quantum system is associated a space of states $H$ which is a Hilbert space. The pure state of the system is then represented by a unit norm vector on such Hilbert space.

The unit of quantum information is the quantum bit a.k.a. Qubit

State of a qubit:

$$|\Psi\rangle = \alpha |0\rangle + \beta |1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$
Postulates of Quantum Computing (1)

Space of states: \( \mathcal{H} \cong \mathbb{C}^2 \)

State of a qubit:

\[
|\psi\rangle = \alpha |0\rangle + \beta |1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}
\]

\( \alpha, \beta \in \mathbb{C} \quad |\alpha|^2 + |\beta|^2 = 1 \)
Postulates of Quantum Computing (1)

Space of states: $\mathcal{H} \cong \mathbb{C}^2$

State of a qubit:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$\alpha, \beta \in \mathbb{C}$  \quad $|\alpha|^2 + |\beta|^2 = 1$

Can be parametrized as:

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

$\theta \in [0,\pi] \quad \phi \in [0,2\pi]$
2. Composite systems
Classically

State of N bits:

\[ |000...0\rangle, |100...0\rangle, |010...0\rangle \ldots |111...1\rangle \]
The space of states of a composite system is the tensor product of the spaces of the subsystems:

$$\mathbb{C}^2 \otimes \mathbb{C}^2 \otimes \ldots \otimes \mathbb{C}^2$$

State of N qubits:

$$\langle 1 | 000\ldots0 \rangle + \langle 2 | 100\ldots0 \rangle + \langle 3 | 010\ldots0 \rangle + \ldots + \langle n | 111\ldots1 \rangle$$

$$d_i \in \mathbb{C} \quad \sum_i |d_i|^2 = 1$$
Quantum Entanglement

States that can be written as tensor product

\[ |\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots \otimes |\psi_n\rangle \]

are called **factorable or product states**
Quantum Entanglement

States that *can NOT* be written as tensor product

\[ |\psi\rangle \neq |\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots \otimes |\psi_n\rangle \]

are called *entangled states*
Quantum Entangled

Example: Schrödinger’s cat
Quantum Entangled

Example: Bell’s states

\[
\frac{1}{\sqrt{2}} \left( |00\rangle + |11\rangle \right) \quad \frac{1}{\sqrt{2}} \left( |01\rangle + |10\rangle \right)
\]

\[
\frac{1}{\sqrt{2}} \left( |00\rangle - |11\rangle \right) \quad \frac{1}{\sqrt{2}} \left( |01\rangle - |10\rangle \right)
\]
3. State Change
### Postulates of Quantum Computing (3)

**Classically: logic gates**

<table>
<thead>
<tr>
<th>Logic Gate</th>
<th>Symbol</th>
<th>Description</th>
<th>Boolean</th>
</tr>
</thead>
<tbody>
<tr>
<td>AND</td>
<td><img src="image" alt="AND Symbol" /></td>
<td>Output is at logic 1 when, and only when all its inputs are at logic 1, otherwise the output is at logic 0.</td>
<td>$X = A \cdot B$</td>
</tr>
<tr>
<td>OR</td>
<td><img src="image" alt="OR Symbol" /></td>
<td>Output is at logic 1 when one or more are at logic 1. If all inputs are at logic 0, output is at logic 0.</td>
<td>$X = A + B$</td>
</tr>
<tr>
<td>NAND</td>
<td><img src="image" alt="NAND Symbol" /></td>
<td>Output is at logic 0 when, and only when all its inputs are at logic 1, otherwise the output is at logic 1.</td>
<td>$X = \overline{A + B}$</td>
</tr>
<tr>
<td>NOR</td>
<td><img src="image" alt="NOR Symbol" /></td>
<td>Output is at logic 0 when one or more of its inputs are at logic 1. If all the inputs are at logic 0, the output is at logic 1.</td>
<td>$X = \overline{A + B}$</td>
</tr>
<tr>
<td>XOR</td>
<td><img src="image" alt="XOR Symbol" /></td>
<td>Output is at logic 1 when one and Only one of its inputs is at logic 1. Otherwise is it logic 0.</td>
<td>$X = A \oplus B$</td>
</tr>
<tr>
<td>XNOR</td>
<td><img src="image" alt="XNOR Symbol" /></td>
<td>Output is at logic 0 when one and only one of its inputs is at logic 1. Otherwise it is logic 1. Similar to XOR but inverted.</td>
<td>$X = A \oplus B$</td>
</tr>
<tr>
<td>NOT</td>
<td><img src="image" alt="NOT Symbol" /></td>
<td>Output is at logic 0 when its only input is at logic 1, and at logic 1 when its only input is at logic 0. That's why it is called an INVERTER.</td>
<td>$X = \overline{A}$</td>
</tr>
</tbody>
</table>
The state change of a closed quantum system is described by a unitary operator

\[ i \frac{d}{dt} |\psi(t)\rangle = H |\psi(t)\rangle \]

\[ |\psi(t)\rangle = e^{-iHT} |\psi(0)\rangle \]

\[ U = e^{-iHT} \]

\[ \psi = |\psi\rangle \]
Quantumly: Quantum Gates

- **X Gate**
  - Bit-flip, Not
  - \[
  \begin{bmatrix}
  0 & 1 \\
  1 & 0 \\
  \end{bmatrix}
  \begin{bmatrix}
  \alpha \\
  \beta \\
  \end{bmatrix}
  =
  \begin{bmatrix}
  \beta \\
  \alpha \\
  \end{bmatrix} = \beta |0\rangle + \alpha |1\rangle
  \]

- **Z Gate**
  - Phase-flip
  - \[
  \begin{bmatrix}
  1 & 0 \\
  0 & -1 \\
  \end{bmatrix}
  \begin{bmatrix}
  \alpha \\
  \beta \\
  \end{bmatrix}
  =
  \begin{bmatrix}
  \alpha \\
  -\beta \\
  \end{bmatrix} = \alpha |0\rangle - \beta |1\rangle
  \]

- **H Gate**
  - Hadamard
  - \[
  \frac{1}{\sqrt{2}}
  \begin{bmatrix}
  1 & 1 \\
  1 & -1 \\
  \end{bmatrix}
  \begin{bmatrix}
  \alpha \\
  \beta \\
  \end{bmatrix}
  =
  \begin{bmatrix}
  \frac{\alpha + \beta}{\sqrt{2}} \\
  \frac{\alpha - \beta}{\sqrt{2}} \\
  \end{bmatrix}
  = \frac{\alpha + \beta |0\rangle + \alpha - \beta |1\rangle}{\sqrt{2}}
  \]

- **T Gate**
  - \[
  \begin{bmatrix}
  1 & 0 \\
  0 & e^{i\pi/4} \\
  \end{bmatrix}
  \begin{bmatrix}
  \alpha \\
  \beta \\
  \end{bmatrix}
  =
  \begin{bmatrix}
  \alpha \\
  \beta e^{i\pi/4} \\
  \end{bmatrix} = \alpha |0\rangle + e^{i\pi/4} \beta |1\rangle
  \]

- **Controlled Not**
  - CNot
  - \[
  \begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & 0 & 1 \\
  0 & 0 & 1 & 0 \\
  \end{bmatrix}
  \begin{bmatrix}
  a \\
  b \\
  c \\
  d \\
  \end{bmatrix}
  =
  \begin{bmatrix}
  a \\
  b \\
  c \\
  d \\
  \end{bmatrix} = a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle
  \]
4. Measurement
Classically

Measuring returns the state of a bit with certainty

\[ |0\rangle \xrightarrow{\text{Measure}} |0\rangle \quad \text{Outcome} \quad |1\rangle \xrightarrow{\text{Measure}} |1\rangle \]

Measurements do not affect the state of a bit
Measuring returns the bit state with some probability

\[ |\psi\rangle = \alpha |0\rangle + \beta |1\rangle \]

 Outcome

 Measure

|0\rangle \quad with \quad P_{0} = |\alpha|^{2}

|1\rangle \quad with \quad P_{1} = |\beta|^{2}

Measurement affects the state of a qubit
To any observable physical quantity is associated an hermitian operator $O$

$$O | \sigma_i \rangle = \sigma_i | \sigma_i \rangle$$

A measurement outcomes are the possibile eigenvalues $\{o_i\}$.

The probability of obtaining $o_i$ as a result of the measurement is

$$P(o_i) = | \langle \psi | \sigma_i \rangle |^2$$

The effect of the measure is to change the state $|\psi\rangle$ into the eigenvector of $O$

$$|\psi\rangle \rightarrow |\sigma_i\rangle$$

When you’re a quantum particle in a state of superposition but you’re about to pass through a detector
Quantum Computing Models
Quantum Computing Models

Gate Model Quantum Computation

Adiabatic Quantum Computation

Measurement Based Quantum Computation

Topological Quantum Computation
Quantum Computing Models

Gate Model Quantum Computation

Adiabatic Quantum Computation

Measurement Based Quantum Computation

Topological Quantum Computation
Quantum Circuits
Quantum Circuits

Quantum Algorithm = Quantum Circuit

A quantum circuit with $n$ input qubits and $n$ output qubits is defined by a unitary transformation

$$U \in U(2^n)$$

$$U^\dagger U = UU^\dagger = I$$

$$U^{-1} = U^\dagger$$
It is necessary to run the circuit and measure multiple times to reconstruct the probability distribution.
Quantum Parallelism
Quantum Parallelism

Oracle: Function evaluation

Given a function \( f : \{0,1\}^N \rightarrow \{0,1\}^M \), an algorithm to evaluate such function is given by the unitary \( U_f \)

\[
|x\rangle |y\rangle \xrightarrow{U_f} |x\rangle |y \oplus f(x)\rangle
\]

where \( x \in \{0,1\}^N \) \( y \in \{0,1\}^M \)
Quantum Parallelism

Consider the following quantum circuit:

\[
\begin{align*}
|0\rangle & \xrightarrow{H} |\text{H}\rangle \\
|0\rangle & \xrightarrow{U_f} \text{output}
\end{align*}
\]
Quantum Parallelism

Quantum Parallelism: step-by-step
Quantum Parallelism

Quantum Parallelism: step-by-step

\[ |0\rangle |0\rangle \xrightarrow{H} \left( \frac{|0\rangle + |1\rangle}{\sqrt{2}} \right) |0\rangle \]

**Hadamard Gate**

\[
\begin{align*}
H|0\rangle &= \frac{1}{\sqrt{2}} \left( |0\rangle + |1\rangle \right) \\
H|1\rangle &= \frac{1}{\sqrt{2}} \left( |0\rangle - |1\rangle \right)
\end{align*}
\]
Quantum Parallelism: step-by-step

$$\begin{align*}
|0\rangle|0\rangle & \xrightarrow{H} \\
& \left( \frac{|0\rangle + |1\rangle}{\sqrt{2}} \right) |0\rangle = \frac{|0\rangle|0\rangle + |1\rangle|0\rangle}{\sqrt{2}}
\end{align*}$$
Quantum Parallelism: step-by-step

\[ |0\rangle |0\rangle \xrightarrow{H} \left( \frac{|0\rangle + |1\rangle}{\sqrt{2}} \right) |0\rangle = \frac{|0\rangle|0\rangle + |1\rangle|0\rangle}{\sqrt{2}} \]

\[ \frac{|0\rangle|0\rangle + |1\rangle|0\rangle}{\sqrt{2}} \xrightarrow{U_f} \frac{|0\rangle f(0) + |1\rangle f(1)}{\sqrt{2}} \]
Quantum Parallelism

Quantum Parallelism: step-by-step

\[ |0\rangle |0\rangle \xrightarrow{H} \left( \frac{|0\rangle + |1\rangle}{\sqrt{2}} \right) |0\rangle = \frac{|0\rangle|0\rangle + |1\rangle|0\rangle}{\sqrt{2}} \]

\[ \frac{|0\rangle|0\rangle + |1\rangle|0\rangle}{\sqrt{2}} \xrightarrow{U_g} \frac{|0\rangle|g(0)\rangle + |1\rangle|g(1)\rangle}{\sqrt{2}} \]
This is a remarkable state!

With a single use of the Oracle, we created a quantum superposition containing information about both $f(0)$ and $f(1)$.

\[ \frac{1}{\sqrt{2}} \left| 0 \right> f(0) + \left| 1 \right> f(1) \]
Quantum Parallelism

This is a remarkable state!

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

With a single use of the Oracle, we created a quantum superposition containing information about both $f(0)$ and $f(1)$.

However, parallelism alone is not immediately useful! Measuring would return a random output (either $f(0)$ or $f(1)$).

Quantum algorithms exploit quantum parallelism to solve some problems faster than classical algorithms.
Quantum Algorithms
Shor Algorithm

Factorization Problem

Given $N$, find the two prime numbers such that

$$N = p \times q$$
Facorization Problem

Given $N$, find the two prime numbers such that

$$N = p \times q$$

Classically: Finding solution requires exponential time

Used in the RSA crypto system
Shor Algorithm

Quantum Algorithm to solve factorization in polynomial time

https://www.youtube.com/watch?v=6qD9XEITpCE
Shor Algorithm

* Assuming we have a fault-tolerant quantum computer capable of executing Shor’s algorithm by applying gates at the speed of current quantum computers based on superconducting circuits.

Number Field Sieve
\[ \exp(1.9 \log(n^{1/3}) \times \log(\log(n))^{2/3}) \]

Time to factor a 2048-digits number

~ billions of years

Shor’s Algorithm
\[ \log(n^3) \]

~ seconds*

* Assuming we have a fault-tolerant quantum computer capable of executing Shor’s algorithm by applying gates at the speed of current quantum computers based on superconducting circuits.
Shor Algorithm

https://www.youtube.com/watch?v=6qD9XEITpCE

The Story of Shor's Algorithm, Straight From the Source | Peter Shor
Grover search algorithm

Run-time brute-force algorithm:

\[ d^N \]

Run-time Grover search:

\[ \sqrt{d^N} \]
Complexity classes

NP-complete

NP
Solution can be verified efficiently

P
Efficient solution

THE MOMENT P=NP IS SOLVED

TO-DOLIST
NOTHING

CINECA
NP-complete
Solution can be verified efficiently

NP
Efficient solution

Complexity classes
NP-complete

Solution can be verified efficiently

NP

Efficient solution

P

Factorization: Shor’s algorithm

Complexity classes
Complexity classes

NP-complete
Solution can be verified efficiently

NP
Solution can be verified efficiently

P
Efficient solution

Search Problems: Grover search

Factorization: Shor’s algorithm
Complexity classes

**NP-complete**
- Solution can be verified efficiently

**NP**
- Shor’s algorithm (Factorization)
- Grover search (Search Problems)

**P**
- Efficient solution

**BQP**
- Efficiently solved by a QC
Complexity classes

- **NP-complete**: Solution can be verified efficiently

- **NP**: Efficient solution

- **P**: Efficiently solved by a QC

- **BQP**: Efficiently solved by a QC

- **Search Problems**: Grover search

- **Factorization**: Shor’s algorithm

- **Quantum systems simulation**
Old School Quantum Algorithms

Cryptography
Shor’s Algorithm
Exponential Speedup

Optimization
Grover’s Algorithm
Quadratic Speedup

Chemistry
Quantum Simulation
Exponential Speedup

Quantum Algorithm Zoo:
https://quantumalgorithmzoo.org/
Old School Quantum Algorithms

Cryptography
Shor’s Algorithm
Exponential Speedup

Optimization
Grover’s Algorithm
Quadratic Speedup

Chemistry
Quantum Simulation
Exponential Speedup

Common sources of errors in QC

- **Coherent quantum errors**: Gates which are incorrectly applied
- **Decoherence**: errors due to the interaction with the environment
- **Initialization errors**: failing to prepare the correct initial state
  - Qubit loss

These algorithms assume to have **ideal qubits** that are not subjected to noise and errors

QEC: introductory guide
https://arxiv.org/abs/1907.11157
Old School Quantum Algorithms: Error correction

Cryptography
Shor’s Algorithm
Exponential Speedup

Optimization
Grover’s Algorithm
Quadratic Speedup

Chemistry
Quantum Simulation
Exponential Speedup

• Require error corrected quantum computers with about 1 million or 100 thousands of qubits
• Error correction comes with an overhead in the number of physical qubits
• Will be available in 10-20 years

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https://arxiv.org/abs/1907.11157
Old School Quantum Algorithms: Error correction

Cryptography
- Shor’s Algorithm
  Exponential Speedup

Optimization
- Grover’s Algorithm
  Quadratic Speedup

Chemistry
- Quantum Simulation
  Exponential Speedup

- Require error corrected quantum computers with about 1 million or 100 thousands of qubits
- Error correction comes with an overhead in the number of physical qubits
- Will be available in 10-20 years

When you see the ratio of physical to logical qubits for fault tolerant quantum computation
How can we use the small and imperfect Quantum Devices (NISQ) we have today?
The NISQ Era
The NISQ Era

NISQ = Noisy Intermediate-Scale Quantum

Intermediate-Scale Quantum computers with no error correction

Different Qubit technologies

Superconducting
Neutral Atoms
Trapped-Ions
Photonic
The NISQ Era

Differences:

Topology: how qubits are connected together

Coherence Time (seconds): quantum superposition lifetime

Gate Delay (seconds): time needed to apply a gate operation

Gate Fidelity (%): Fidelity in gate operation
### Qubit technologies

<table>
<thead>
<tr>
<th></th>
<th>Superconducting</th>
<th>Superconducting</th>
<th>Superconducting</th>
<th>Superconducting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subtype</strong></td>
<td>Tunable</td>
<td>Fixed Freq.</td>
<td>Parametric</td>
<td>Flux</td>
</tr>
<tr>
<td><strong>Coherence Time</strong></td>
<td>1.50E-05</td>
<td>1.50E-04</td>
<td>2.00E-05</td>
<td>5.00E-08</td>
</tr>
<tr>
<td>(seconds)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gate Fidelity (%)</strong></td>
<td>99.7%</td>
<td>99.1%</td>
<td>99.2%</td>
<td></td>
</tr>
<tr>
<td><strong>Gate Delay</strong></td>
<td>2.0E-08</td>
<td>4.50E-07</td>
<td>1.60E-07</td>
<td></td>
</tr>
<tr>
<td>(seconds)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>20mK</td>
<td>20mK</td>
<td>20mK</td>
<td>20mK</td>
</tr>
<tr>
<td><strong>Largest Device</strong></td>
<td>53Q</td>
<td>127Q</td>
<td>80Q</td>
<td>5000Q</td>
</tr>
<tr>
<td><strong>Players</strong></td>
<td>Google QuTech</td>
<td>IBM OpenSuperQ</td>
<td>Rigetti</td>
<td>D-Wave Qilimanjaro</td>
</tr>
<tr>
<td></td>
<td>Quantum Circuits Inc.</td>
<td>OQC</td>
<td>Bleximo</td>
<td>Qilimanjaro</td>
</tr>
<tr>
<td></td>
<td>IQM</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>SeeQC</td>
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</tr>
</tbody>
</table>

**Pros:** High gate speeds and fidelities. Can leverage standard lithographic processes. Among first qubit modalities so has a head start.

**Cons:** Requires cryogenic cooling; short coherence times; microwave interconnect frequencies still not well understood.
# Qubit technologies

<table>
<thead>
<tr>
<th></th>
<th>Trapped Ions</th>
<th>Trapped Ions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subtype</strong></td>
<td>Hyperfine</td>
<td>Optical</td>
</tr>
<tr>
<td><strong>Coherence Time (seconds)</strong></td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Gate Fidelity (%)</strong></td>
<td>99.92%</td>
<td>99.6%</td>
</tr>
<tr>
<td><strong>Gate Delay (seconds)</strong></td>
<td>2.00E-04</td>
<td>2.0E-04</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Vacuum</td>
<td>Vacuum</td>
</tr>
<tr>
<td><strong>Largest Device</strong></td>
<td>32Q</td>
<td>20Q</td>
</tr>
<tr>
<td><strong>Notable Players</strong></td>
<td>IonQ Honeywell</td>
<td>AQT AQTION NextGenQ</td>
</tr>
</tbody>
</table>

**Pros:** Extremely high gate fidelities and long coherence times. Extreme cryogenic cooling not required. Ions are perfect and consistent.

**Cons:** Slow gate times/operations and low connectivity between qubits. Lasers hard to align and scale. Ultra-high vacuum required. Ion charges may restrict scalability.
## Qubit technologies

<table>
<thead>
<tr>
<th></th>
<th>Photonics</th>
<th>Photonics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subtype</strong></td>
<td>$\text{Si}_3\text{N}_4$</td>
<td>Other</td>
</tr>
<tr>
<td><strong>Coherence Time (seconds)</strong></td>
<td>$1.50\times10^{-4}$</td>
<td></td>
</tr>
<tr>
<td><strong>Gate Fidelity (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gate Delay (seconds)</strong></td>
<td>$1.00\times10^{-9}$</td>
<td></td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Ambient, 2K only for Detectors</td>
<td>Ambient, 2K only for Detectors</td>
</tr>
<tr>
<td><strong>Largest Device</strong></td>
<td>216 continuos variable Qumode</td>
<td>20 photons</td>
</tr>
<tr>
<td><strong>Notable Players</strong></td>
<td>Xanadu, QuiX</td>
<td>PsiQ, Orca Computing</td>
</tr>
</tbody>
</table>

**Pros**: Extremely fast gate speeds and promising fidelities. No cryogenics or vacuums required. Small overall footprint. Can leverage existing CMOS fabs.

**Cons**: Noise from photon loss; each program requires its own chip. Photons don’t naturally interact so 2Q gate challenges.

[https://quantumcomputingreport.com/](https://quantumcomputingreport.com/)
# Qubit technologies

<table>
<thead>
<tr>
<th></th>
<th>Neutral Atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherence Time (seconds)</td>
<td>$3.20E-01$</td>
</tr>
<tr>
<td>Gate Fidelity (%)</td>
<td>Expected to be around 98%</td>
</tr>
<tr>
<td>Gate Delay (seconds)</td>
<td>$1.00E-06$</td>
</tr>
<tr>
<td>Environment</td>
<td>Vacuum</td>
</tr>
<tr>
<td>Largest Device</td>
<td>200Q</td>
</tr>
<tr>
<td>Notable Players</td>
<td>- ColdQuanta&lt;br&gt;- QuEra&lt;br&gt;- Pasqal&lt;br&gt;- Atom Computing</td>
</tr>
</tbody>
</table>
Qubit technologies

Can be easily emulated on a laptop (<20 qubits), server (<30) or server cluster (<40 qubits)

Qubit technologies

interesting (currently empty) NISQ zone
narrow window of potential NISQ usefulness
too noisy to be useful at scale

Researching & Developing the Computers of Tomorrow Requires Powerful Simulations Today

Qubits can be easily emulated on a laptop (<20 qubits), server (<30) or server cluster (<40 qubits)

average two-qubit gate error rates

The NISQ Era

NISQ = Noisy Intermediate-Scale Quantum

Intermediate-Scale Quantum computers with no error correction

- General Purpose QC
- Quantum Simulator
- Quantum Annealers
The NISQ Era

Quantum Annealers

Can only run Quantum annealing algorithm

Intermediate-Scale:
Up to several thousands of qubits

D-Wave Advantage:
5000 qubits

Noise:

- No need for Quantum Error Correction
- Still unclear: noise due to qubit quality could affect scalability (i.e. performance related to large problems)
The NISQ Era

Quantum Annealers

- Can be used to solve problems expressed as QUBO or Ising

\[ \sum_i h_i \sigma_i^z + \sum_{i<j} J_{ij} \sigma_i^z \sigma_j^z \]

- Use Quantum Tunnelling and Superposition to explore the configuration space

The NISQ Era

Quantum Annealers

Several real-world hard problems can be formulated as QUBO problems

Ising formulation of NP problems: https://arxiv.org/abs/1302.5843

Machine Learning


Molecular Dynamics

https://arxiv.org/abs/2107.13607

Scheduling

Quantum Annealers

- Could have advantage over classical techniques like Simulated Annealing

The transition probability in SA is proportional to

\[ e^{-\frac{\Delta}{k_B T}} \]

In QA, the strength of transverse field determines the probability of quantum tunneling. The transition probability is proportional to

\[ e^{-\frac{\sqrt{\Delta w}}{\Gamma}} \]

with \[ w \ll \sqrt{\Delta} \]
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 used to manipulate quantum state
- Qubit register **topology**

The NISQ Era

Can implement a limited set of algorithms

Intermediate-Scale:
Up to hundreds of qubits

Pasqal: 100 Qubits
QuEra: 200 Qubits

Quantum Simulator

Noise:
• No Quantum Error Correction: overhead in number of qubit
• Interaction with environment generates errors, this limits the duration of quantum computation
The NISQ Era

**General Purpose QC**

Use gates, in theory can run any quantum algorithm

Intermediate-Scale:
Up to hundreds of qubits

**IBM:** 127 Qubits
**Google:** 72 Qubits

**Noise:**
- No Quantum Error Correction:
  overhead in number of qubit
- Error rate per single gate affects the depth of the circuit:
  error rate of 0.1% means that we can run circuits with at most 100 elementary gates (shallow circuits)
Quantum algorithms for NISQ Devices
Quantum algorithms for NISQ Devices

NISQ-ready algorithms

The scientific community believes that NISQ technology could outperform traditional classical computers for specific applications:

- Speed up
- Better quality solutions
- Lower energy consumption
- Quantum Chemistry
- Quantum Optimization
- Quantum AI/Machine Learning

Beyond quantum supremacy:
https://www.nature.com/articles/d41586-019-02936-3
Quantum algorithms for NISQ Devices

**Quantum Supremacy:** demonstrating that a programmable quantum device can solve a problem that no classical computer can solve in any feasible amount of time.

In 2019, researchers at the Google Quantum AI Lab compared the performance of quantum computers to classical supercomputers, using their *Sycamore quantum computer* with *53 qubits*.

https://www.nature.com/articles/s41586-019-1666-5
Quantum Supremacy: with just 53 qubits, their Sycamore quantum computer was able to run a specific algorithm, called the Random Quantum Circuit (RQC), in 200 seconds. Much less than the 2.5 days estimated to perform the same calculation with most powerful supercomputer.

https://www.nature.com/articles/s41586-019-1666-5
NASA and Google researchers, used a program called qFlex, believed to be the most efficient classic emulator quantum system to implement the RQC algorithm on one of the most powerful supercomputers in the world, Summit.

The qFlex implementation required 21 MWh on Summit, while the problem solved by Sycamore device used only 0.42 kWh.

[Link to the paper](https://arxiv.org/abs/1811.09599)
Quantum algorithms for NISQ Devices

NISQ-ready algorithms

The scientific community believes that NISQ technology could outperform traditional classical computers for specific applications.

- Speed up
- Better quality solutions
- Lower energy consumption

- Quantum Chemistry
- Quantum Optimization
- Quantum AI/Machine Learning
Random Quantum Circuit (RQC) does not solve any useful (real-world) problem. Its purpose is exactly to prove Quantum supremacy.
Quantum algorithms for NISQ Devices

Hybrid Quantum-Classical algorithms

Quantum algorithms for NISQ Devices

Parametric Quantum Circuits

- Circuits that **use gates**, or in general, that apply **parameter-dependent operations** to qubits (e.g. Arbitrary rotations of angle $\gamma$)

- **Shallow circuits**, i.e. of **limited depth** (1000 gates maximum, due to limited coherence times)

- Circuits in which the **error is not corrected**

  But **errors can be mitigated**
Quantum algorithms for NISQ Devices

Variational Quantum Algorithms:
Quantum algorithms for NISQ Devices

Working principle

1. Choose the parametric circuit you want to use (Variational Ansatz)

2. Implement Variational Ansatz on the QPU

Quantum algorithms for NISQ Devices

Working principle

1. Choose the parametric circuit you want to use (Variational Ansatz)

2. Implement Variational Ansatz on the QPU

3. Measure the qubits and calculate the cost function

\[ E_\theta = \langle \Psi(\hat{\theta}) | H | \Psi(\hat{\theta}) \rangle \]

Variational Quantum Algorithms:
Quantum algorithms for NISQ Devices

Working principle

Variational Quantum Algorithms:
Quantum algorithms for NISQ Devices

Working principle

1. Choose the parametric circuit you want to use (Variational Ansatz)

2. Implement Variational Ansatz on the QPU

3. Measure the qubits and calculate the cost function

4. Use a classic computer to optimize the circuit parameters

The optimization of the set of parameters could be gradient-based or gradient-free (BFGS, COBYLA, L-B, SPSA, Bayesian Opt.) Depending on the type of cost function being evaluated

Quantum algorithms for NISQ Devices

Working principle

1. Choose the parametric circuit you want to use (Variational Ansatz)
2. Implement Variational Ansatz on the QPU
3. Measure the qubits and calculate the cost function
4. Use a classic computer to optimize the circuit parameters

This cycle is repeated until convergence. The final state gives us an approximation of the solution.

Heuristic Algorithm

Quantum algorithms for NISQ Devices

Variational Quantum Algorithms:

Working principle

4. Classical optimization of parameters gamma

Quantum algorithms for NISQ Devices

Variational Quantum Algorithms:
Quantum algorithms for NISQ Devices

VQE

Quantum Chemistry

QAOA

Quantum Optimization

QSVM & QNN

Quantum Machine Learning
The main difference between VQE, QAOA and QML concerns the choice of the parametric quantum circuit (Variational Ansatz).
Quantum algorithms for NISQ Devices

Variational Quantum Eigensolver (VQE)

Quantum algorithms for NISQ Devices

Variational Quantum Eigensolver (VQE) – QUANTUM CHEMISTRY

**Objective**: finding the ground state energy of molecules

Quantum algorithms for NISQ Devices

Variational Quantum Eigensolver (VQE) – QUANTUM CHEMISTRY

**Objective:**

to calculate the ground state of molecules

**Method:**

Ansatz is a provisional molecular ground state

**Possible Advantage:**

Simulate complex quantum molecular wavefunctions in polynomial time

https://arxiv.org/abs/1704.05018
Quantum algorithms for NISQ Devices

Variational Quantum Eigensolver (VQE) – Ansatz

VQE uses:

Chemical-inspired Ansatz, such as the Unitary Coupled Cluster (UCC) method

(Challenge: may be harder to implement on real hardware)

or a Hardware-efficient Ansatz

(Challenge: easy to implement on hardware but lack of any physical meaning)

https://arxiv.org/abs/1704.05018
Quantum algorithms for NISQ Devices

Quantum Approximate Optimization Algorithm (QAOA)

LOOK AT ALL THESE

QUANTUM APPLICATIONS
Quantum algorithms for NISQ Devices

Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

Optimization Problems

Routing

Scheduling

Portfolio Optimization
Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

**Objective**: to solve a combinatorial optimization problem

**Method**: Ansatz encodes two alternating circuits, $U(C)$ and $U(B)$, each parameterized by a number, $\gamma$ and $\beta$.

Ideally, the circuit provides the solution $|\gamma, \beta\rangle$ to a combinatorial problem implicit in the definition of $U(C)$.

A Quantum Approximate Optimization Algorithm: https://arxiv.org/abs/1411.4028
Quantum algorithms for NISQ Devices

Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

\[ |\gamma, \beta\rangle = U(B, \beta_p) U(C, \gamma_p) \cdots U(B, \beta_1) U(C, \gamma_1) |s\rangle \]

- **solution**
- **Circuit (alternating circuits)**
- **initial state**

\[ U(C, \gamma) = e^{-i\gamma C} = \prod_{\alpha=1}^{m} e^{-i\gamma C_\alpha} \]

**Encodes the optimization problem** to solve (e.g. C could be some Qubo problem)

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

**Possible Advantage:**

Allow the **quantum exploration of the solution space**
Quantum algorithms for NISQ Devices

Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

**Challenge**: find a class of problems for which QAOA is strictly better than the best classical algorithms.

A Quantum Approximate Optimization Algorithm: https://arxiv.org/abs/1411.4028
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML)
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum Feature Map

Quantum Feature map
maps classical vector into a quantum state

\[ \tilde{\mathbf{x}} \mapsto |\Phi(\tilde{\mathbf{x}})\rangle = U_{\Phi(\tilde{\mathbf{x}})} |0\rangle^{\otimes n} \]

Quantum enhanced feature spaces:
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum SVM

Quantum Kernel

\[ K(\tilde{x}_i, \tilde{x}_j) = |\langle \Phi(\tilde{x}_i) | \Phi(\tilde{x}_j) \rangle|^2 = |\langle 0 | \mathcal{U}^{\dagger}_\Phi(\tilde{x}_j) \mathcal{U}_\Phi(\tilde{x}_i) | 0 \rangle \otimes n \rangle |^2 \]

**Goal**: Address a classification problem (like classical SVMs)

**Challenge**: More complex feature map at low computational cost

Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum NN

**Goal**: Address a supervised machine learning problem

**Method**: Ansatz consists of a feature map that serves to represent classical data and a variational part for learning

- **Feature map**: Store the inputs in a quantum state
- **Variational circuit**: Learnable parameter circuit
- **Expectation value**: Measurements introduce non-linearity

The power of quantum neural networks
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum NN

The Power of QNNs

More evenly spread eigenvalues of the Fisher information for the QNN wrt classical NN with same number of parameters

Better Generalization (how accurately the algorithm is able to predict outcome values for previously unseen data.)

The power of quantum neural networks
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum NN

Barren Plateaus: Vanishing loss function Gradient that make it hard to train the QNN

Features that may induce Barren Plateaus

Subtleties in the trainability of QML models:
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum NN

Re-Uploading QNN
Universal function approximator

Convolutional QNN
Absence of Barren Plateaus

Dissipative QNN
Backpropagation-like training
https://arxiv.org/abs/1902.10445

Quantum computing models for NN
https://arxiv.org/abs/2102.03879
QUANTUM ADVANTAGE IN THE NISQ ERA?
# Quantum algorithms for NISQ Devices

## NISQ gate-based hardware resource requirements

<table>
<thead>
<tr>
<th>resources</th>
<th>initial estimates</th>
<th>realistic estimates and constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>qubit number</em></td>
<td>50 qubits for a computational advantage (Preskill)</td>
<td>100s to 1000s qubits for many practical NISQ algorithms to obtain a speedup advantage (Guerreschi, Albino).</td>
</tr>
<tr>
<td><em>computing depth</em></td>
<td>use shallow algorithms with under 10-gate cycles</td>
<td>most NISQ algorithms in the quantum advantage regime have &gt;100s gate cycles</td>
</tr>
<tr>
<td><em>available fidelities</em></td>
<td>NISQ is to use currently available qubit fidelities that are in the 99.9% to 99% range</td>
<td>current QPs either have low fidelities and &gt;30 qubits (transmons) or better fidelities and &lt;30 qubits (trapped ions)</td>
</tr>
<tr>
<td><em>required fidelities</em></td>
<td>error rate $\ll \frac{1}{\text{# qubits} \times \text{algo depth}}$ for QAOA, but seemingly for other NISQ algorithms as well</td>
<td>the fidelities requirements are not matched by actual hardware even for the shallowest computing depth</td>
</tr>
<tr>
<td></td>
<td>for QAOA, but seemingly for other NISQ algorithms as well</td>
<td>1/(1121 q * 8 d) =&gt; 99,99% possible?</td>
</tr>
<tr>
<td></td>
<td><a href="https://arxiv.org/ftp/arxiv/papers/2305/2305.09518.pdf">https://arxiv.org/ftp/arxiv/papers/2305/2305.09518.pdf</a></td>
<td>1/(1127 q * 8 d) =&gt; 99,9% IBM Heron’s 133 qubit GPU in 2024?</td>
</tr>
<tr>
<td></td>
<td>error rate usually relates to the two-qubit error rate, which should ideally be its minimum error rate and not median/average rate.</td>
<td>1/(65 q * 8 d) =&gt; 99,8% not available.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1/(53 q * 8 d) =&gt; 99,7% Google Sycamore is at 98,6%.</td>
</tr>
</tbody>
</table>

*minimum ansatz depth of 8 gate cycles*
Quantum Computing Software
Quantum Computing software

The quantum stack

**CONTROL LOGIC**
- Pulse & timing calibration
- Optimal Control
- Decoding

**CONTROL PLANE**
- Crosstalk
- Wiring/integration
- Heat management

**QUANTUM PLANE**
- Fidelity
- Native gates
- Connectivity
- Interconnects

**SIMULATOR**
- Verification & validation
- Performance

**APPLICATIONS**
- Development mgt.
- Workflow mgt.

**ALGORITHMS**
- High level languages
- Libraries

**FRAMEWORK**
- Circuit model & alternatives
- Optimising compilers

**ARCHITECTURE**
- QPU kernel
- Quantum error correction
- Magic state factories
- QRAM

https://quantumcomputingreport.com/
Quantum Computing software

Early gate-model full-stack players

IBM Quantum
- IBM Q Network
- Qiskit-Nature
- Python
- Qiskit Terra
- Cirq
- OpenFermion

Google QCS
- Early Access Program
- Python
- Qiskit Runtime
- Cirq
- QVM

Rigetti QCS
- Grove
- pyQuil
- QVM

Xanadu
- TensorFlow
- PyTorch
- NumPy
- Strawberry Fields
- Blackbird
- QVM

OriginQ Cloud
- Industry Alliance
- C++
- ChemiQ
- QPanda
- QRunes

Pasqal
- Pulser
- Python
- QuTiP based

https://quantumcomputingreport.com/
Quantum Computing software

Quantum PaaS (Platform as a Service)

IBM Quantum
- IBM Q Network
- Python
- Qiskit-Nature
- Qiskit Terra
- OpenQASM
- Qiskit Runtime
- Rigetti
- IonQ
- OQC
- QCI
- QDK Simulator

Amazon Braket
- AWS Cloud
- Python
- PennyLane
- Ocean
- Braket
- Rigetti
- IonQ
- QCI
- QIR
- Toshiba
- QDK Simulator

Azure Quantum
- Azure Cloud
- Visual Studio
- Q#
- Q# Libs
- QIR
- Toshiba
- Quantum Engine

Google QCS
- Early Access Prog.
- Python
- Qsim
- Cirq
- Google

https://quantumcomputingreport.com/
Projects and Fundings
Projects and Fundings

Startup and Private companies

**Figure 4** Map of start-ups in quantum computing

- **$440 million** invested in software from 2010 to 2019
- **$764 million** invested in software from 2020 to 2021


Source: Boston Consulting Group, adapted from PitchBook, 2021

Projects and Fundings

Public investments

Map of global public investments in quantum technologies

Global effort:
30 Billion dollars

Source: QUlECA, 2022
Projects and Fundings

Public investments

Announced planned governmental funding, $ billion

<table>
<thead>
<tr>
<th>Country</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>15.3</td>
</tr>
<tr>
<td>European Union</td>
<td>7.2</td>
</tr>
<tr>
<td>United States</td>
<td>1.9</td>
</tr>
<tr>
<td>Japan</td>
<td>1.8</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>1.3</td>
</tr>
<tr>
<td>India</td>
<td>1.0</td>
</tr>
<tr>
<td>Canada</td>
<td>1.0</td>
</tr>
<tr>
<td>Russia</td>
<td>0.7</td>
</tr>
<tr>
<td>Israel</td>
<td>0.5</td>
</tr>
<tr>
<td>Singapore</td>
<td>0.3</td>
</tr>
<tr>
<td>Australia</td>
<td>0.2</td>
</tr>
<tr>
<td>Other</td>
<td>0.1</td>
</tr>
</tbody>
</table>

EU public funding sources, %

- Germany: 41.9%
- France: 28.0%
- European Union: 14.0%
- Netherlands: 11.9%
- Others: 1.7%

Source: McKinsey & Company, adapted from Johnny Kung and Muriel Fancy, 2021

Projects and Fundings

- **May 2016**: The Manifesto, addressed to the European Commission, said in essence: we have the opportunity to compete for a new kind of technological independence, let’s take it.

- **October 2018**: The European Commission launched the Quantum Flagship program: 1.3 billions of Euro to support 10 year of quantum technologies research and development.

- The **European High Performance Computing Joint Undertaking** (EuroHPC JU) is a joint initiative between the EU, European countries and private partners to develop a World Class Supercomputing Ecosystem in Europe.

- The **European Processor Initiative (EPI)** is a project whose aim is to design and implement a roadmap for a new family of low-power European processors for extreme scale computing, high performance Big-Data and a range of emerging applications.
The HPCQS consortium was born with the idea of combining HPC and QC hardware and software.

For the realization of Quantum Computers, the French company PASQAL was chosen, which produces quantum computers based on Neutral Atoms technology.

During the 4 years of the project, the most efficient way to connect Pasqal computers to EuroHPC supercomputers will be studied.

The ultimate goal of the project is the creation of an interconnected network of quantum computers throughout Europe, able to communicate with each other and through the support of EUROHPC supercomputers.

https://www.hpcqs.eu/
Modular Supercomputer Architecture

- **Integrate the QPU** as a new module into the supercomputer
- **Low-latency connection** to other modules via federated, high-speed network
- Integration in the **scheduling and resource management** on the system level
Projects and Fundings

- Candidate EuroHPC exascale site installing HPCQS hybrid
- EuroHPC pre-exascale site
- Tier-1 supercomputer center
- Public pilot user site
- Industrial pilot user site
- Software company

<table>
<thead>
<tr>
<th>FZJ (Coordinator)</th>
<th>CNRS</th>
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<tbody>
<tr>
<td>ParTec (LTP¹)</td>
<td>Sorbonne (LTP*)</td>
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<tr>
<td>CEA</td>
<td>SUPELEC (LTP*)</td>
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<td>GENCI</td>
<td>INRIA</td>
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<td>Parity QC</td>
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<td>Fraunhofer IAF</td>
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</table>
Projects and Fundings: ITALY

- **ISCRA-C**: Quantum Computing as a Service

- **D-Wave Quantum Annealer**
  - Since 01/03/2021 possibility to request calculation hours to be used on D-Wave quantum machines
  - More than 15 projects already approved (almost fully allocated monthly calculation hours budget)

- **Scientific collaboration with Pasqal**
  - On 03/15/2021 start of scientific collaboration with Pasqal's Neutral Atoms simulation systems
  - Preliminary preparation phase for future collaboration

https://www.hpc.cineca.it/services/iscra
Projects and Fundings

The EuroHPC JU has selected six sites across the European Union to host and operate the first EuroHPC quantum computers in:

- Czechia
- France
- Germany
- Italy
- Poland
- Spain

Thanks

I hope you don’t feel like this..
Quantum Computing @ CINECA

CINECA: Italian HPC center
CINECA Quantum Computing Lab:
- Support research Universities, Industries and QC startups
- Internship programs, Courses and Conference (HPCQC)

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