Incontri introduttivi al Quantum Computing

Calcolatori e simulatori quantistici nella NISQ era – cosa sono e cosa possono fare

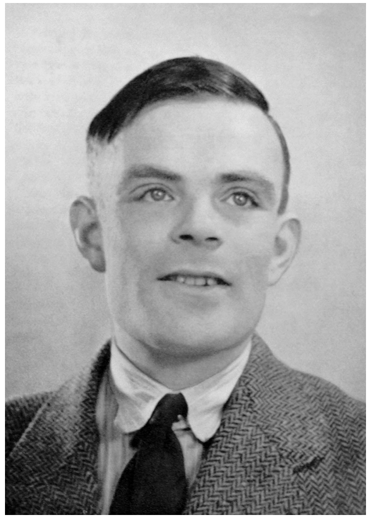
Ilaria Siloi (Unipd)

QUANTUM
COMPUTING
AND
SIMULATION
CENTER

14 marzo 2023

First steps in computer science

1936 Turing Machine



Alan Turing (1912-1954)

The abstract notion of a programmable and universal computer

Church-Turing thesis: equivalence between the class of algorithms performed on some physical device with the rigorous mathematical concept of universal Turing Machine.

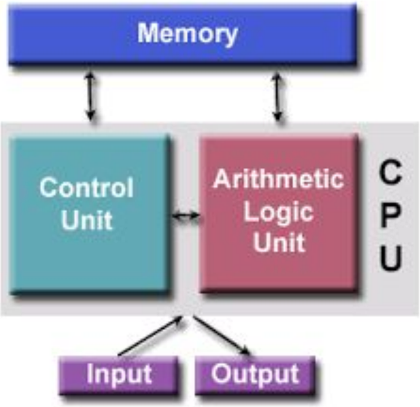
Ex: Turing tape (memory) divided in cells. The control unit moves and executes basic operations (i.e. reading/writing/erasing). Any computable quantity is obtained in a finite number of steps.

1945 Von Neumann architecture

A theoretical model for practical design of a universal Turing Machine:

- Control Unit: fetches instructions/data from memory
- Arithmetic Logic Unit: basic arithmetic operations
- Memory: store data and instructions
- I/O

John Von Neumann (1905-1957)



1947 Bardeen, Brattain, Shockley

Hardware development with transistor!

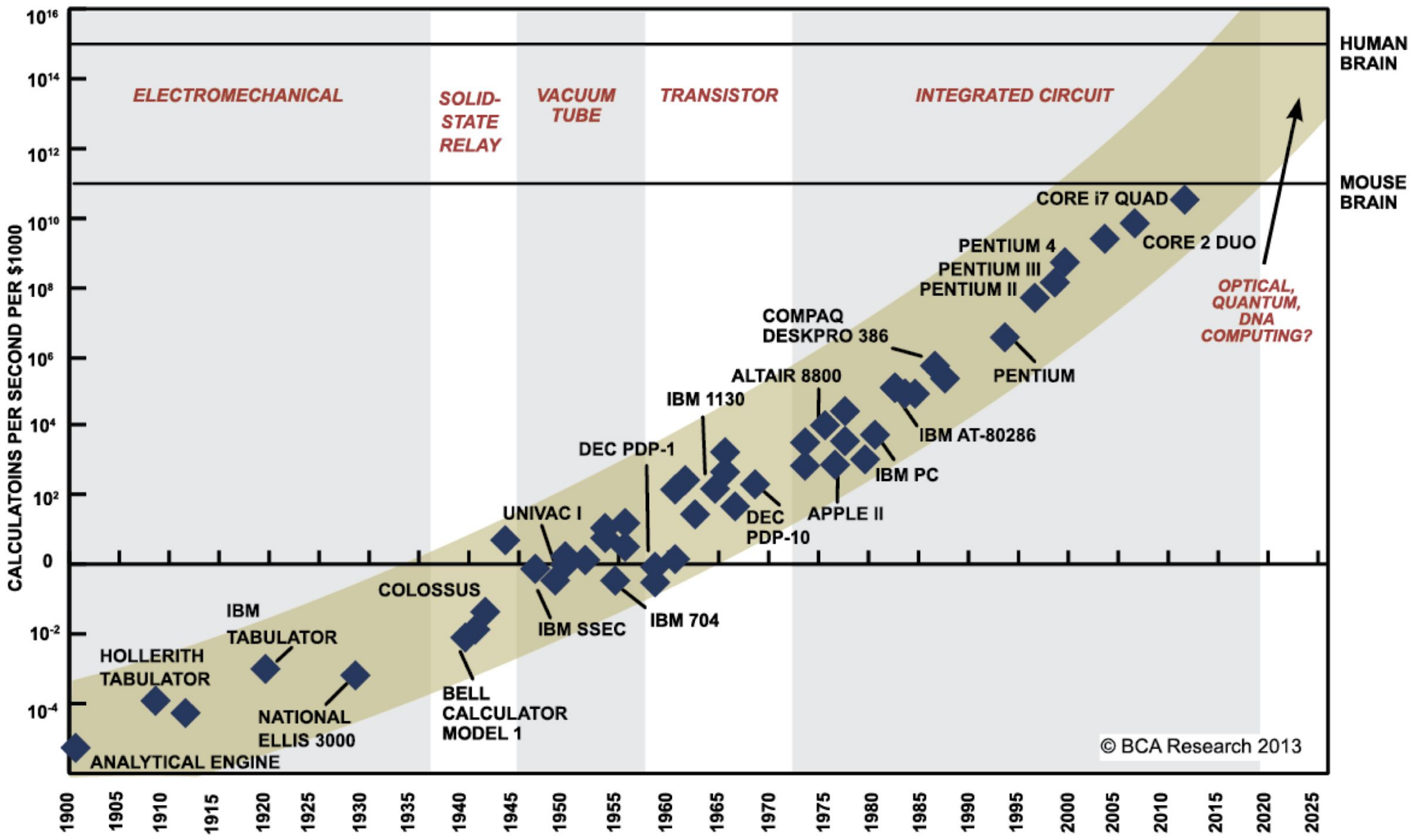
Why quantum computing?

1965 Moore law

- Computer power double for a constant cost every two years (since 1960)

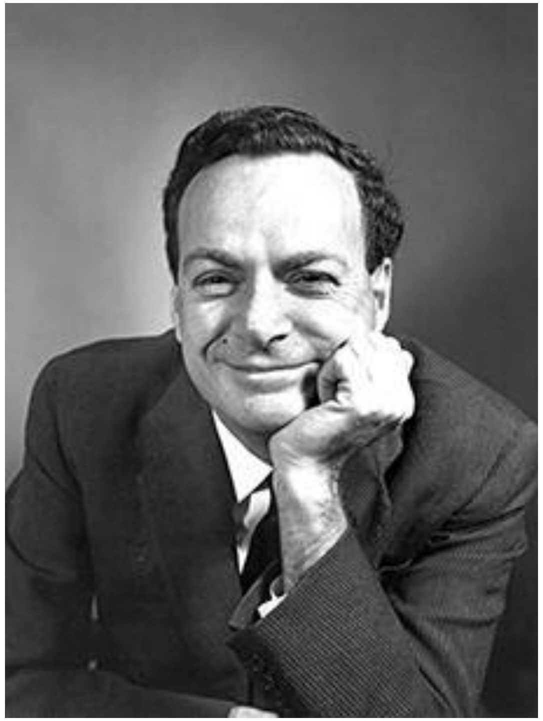
PLATEAU

- Expensive and difficult nanofabrication techniques (<10nm!!)
- Quantum effects are no longer negligible



SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

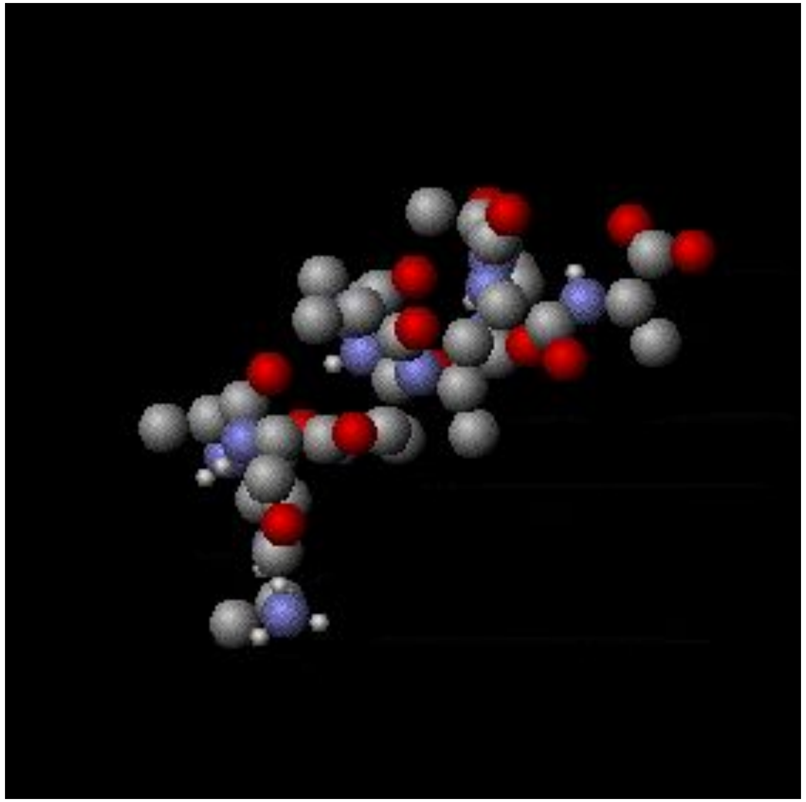
Quantum Simulators & Universal Quantum Computers



Richard Feynmann (1912-1954)

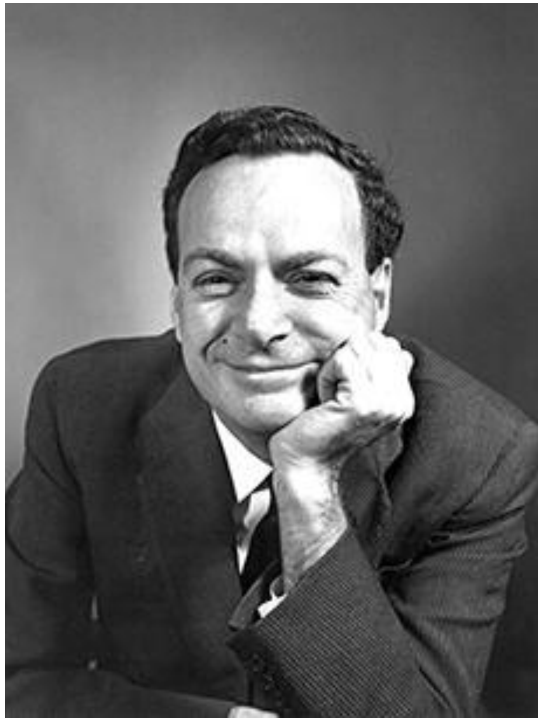
1982 Quantum Simulators

- At the atomic (sub-atomic) scale, Nature obeys to quantum mechanical laws
- Simulating quantum mechanical systems with ordinary computer is *not efficient*
- By quantum simulator, we understand a controllable quantum system used to simulate or emulate other quantum systems. Quantum simulators mimic quantum processes.



R. Feynman, International Journal of Theoretical Physics volume 21, pages 467–488 (1982)

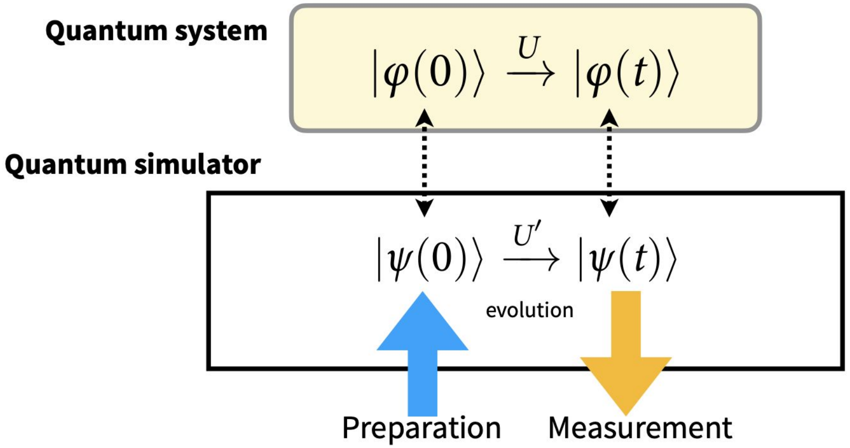
Quantum Simulators & Universal Quantum Computers

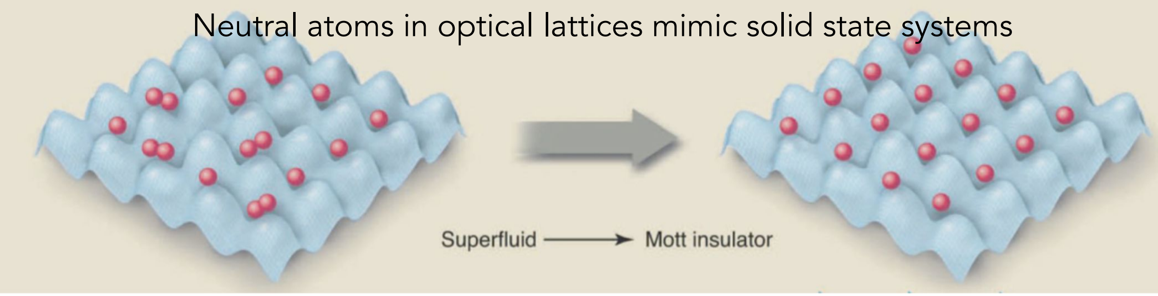


Richard Feynman (1912-1954)

1982 Quantum Simulators

- At the atomic (sub-atomic) scale, Nature obeys to quantum mechanical laws
- Simulating quantum mechanical systems with ordinary computer is *not efficient*
- By quantum simulator, we understand a controllable quantum system used to simulate or emulate other quantum systems. Quantum simulators mimic quantum processes.

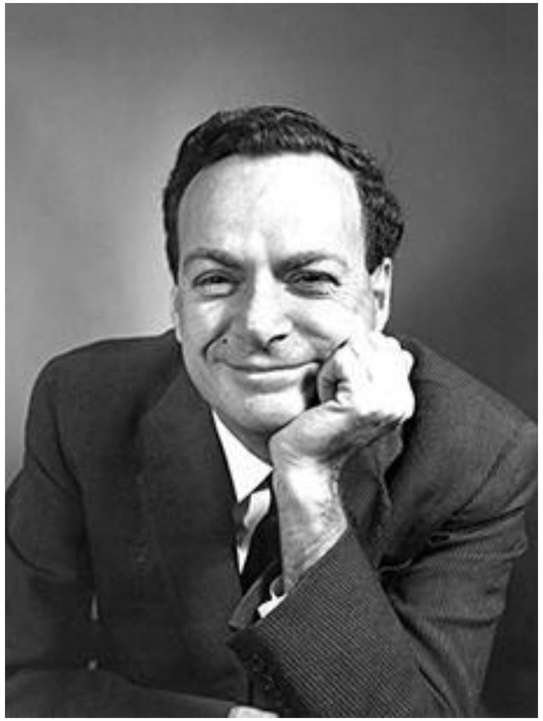




Neutral atoms in optical lattices mimic solid state systems

R. Feynman, International Journal of Theoretical Physics volume 21, pages 467–488 (1982)

Quantum Simulators & Universal Quantum Computers



Richard Feynmann (1912-1954)

1982 Quantum Simulators

- At the atomic (sub-atomic) scale, Nature obeys to quantum mechanical laws
- Simulating quantum mechanical systems with ordinary computer is *not efficient*
- By quantum simulator, we understand a controllable quantum system used to simulate or emulate other quantum systems. Quantum simulators mimic quantum processes.

R. Feynman, International Journal of Theoretical Physics volume 21, pages 467–488 (1982)

1985 Universal Quantum Computer

- Using the laws of quantum mechanics to define a quantum Turing machine?
- Universal Quantum Computer is an abstract machine used to model the effects of a quantum computer: any quantum algorithm can be expressed as a quantum Turing Machine.
- A Universal Quantum Computer efficiently solves computational problems which have no efficient solution on a classical computer.

David Deutsch (1953)

Deutsch, David. "Quantum theory, the Church–Turing principle and the universal quantum computer." *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences*400.1818 (1985): 97-117.

Quantum algorithms

Peter Shor(1959)

1994 Shor's algorithm

- On a quantum computer finding the prime factors of an integer is exponentially faster than any classical algorithm known so far.
- Prime factoring is at the core of many encryption scheme (i.e. RSA)
- Indication for quantum computer to be more powerful than classical computers

1995 Grover's algorithm

- Conducting search through some unstructured database is polynomially faster on quantum computer
- It needs to call a black box function $O(N^{1/2})$ times.
- Widespread applicability (constrained satisfaction problems, 3SAT …)

Lov Grover (1961)

Shor, Peter W. "Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer." *SIAM review* 41.2 (1999): 303-332.

Grover, Lov K. "A fast quantum mechanical algorithm for database search." *Proceedings of the twenty-eighth annual ACM symposium on Theory of computing*. 1996.

Where are we now with quantum computing?

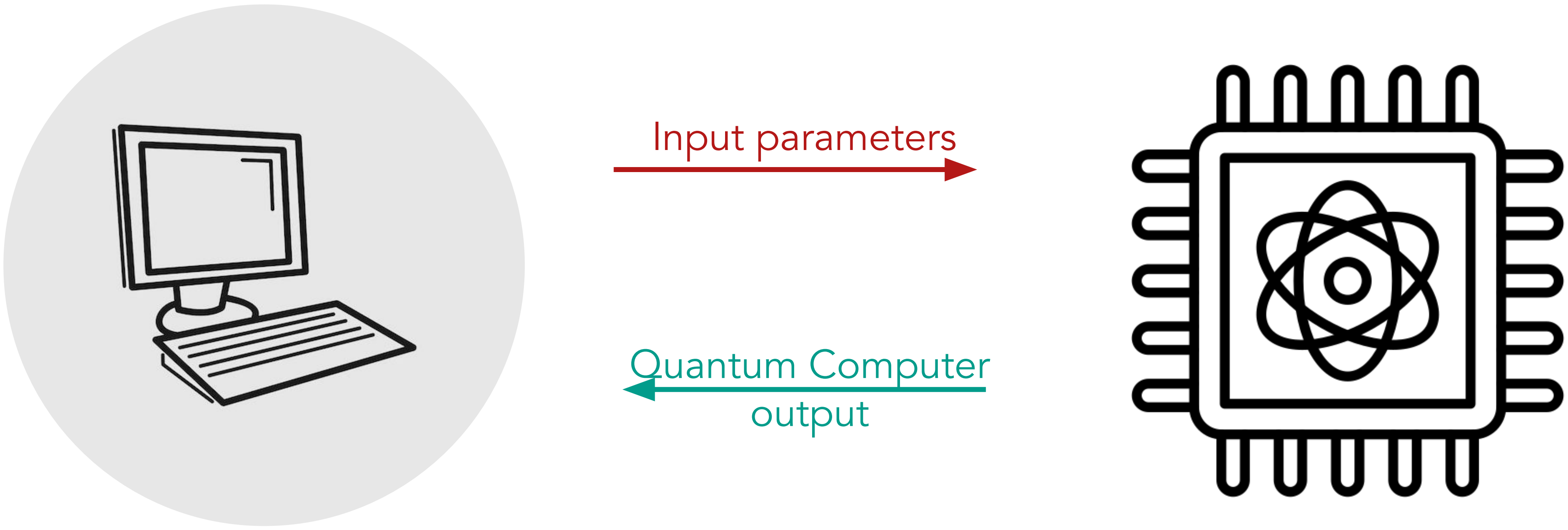
Noisy Intermediate Scale Quantum Computers (NISQ)

- Limited number of qubits n~20-400
- Hardly controllable systems;
- Too many errors in logical
- Error correction is not possible gates ~ $O(10^{-3}/10^{-4})$

- Application to real-world problems;
- Proving quantum advantage

https://quantumalgorithmzoo.org/

Hybrid quantum-classical algorithms



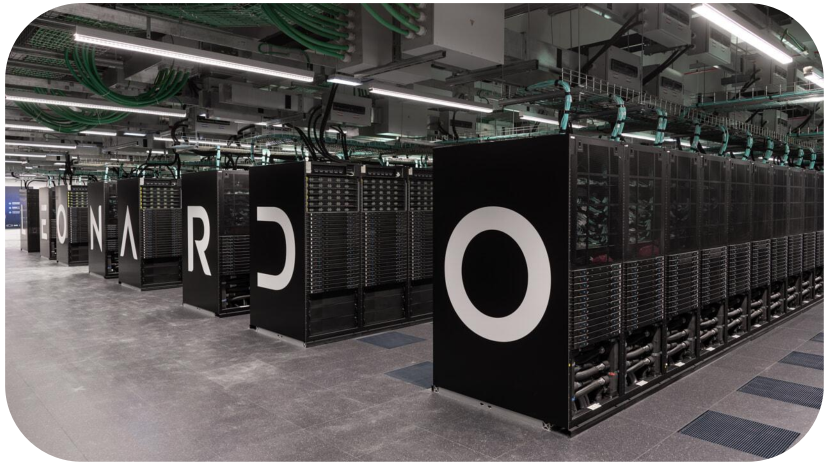
Input parameters

Quantum Computer output

Memory available instead of QC
Doesn't solve efficiently certain tasks

Solve hard problems with quantum algorithms

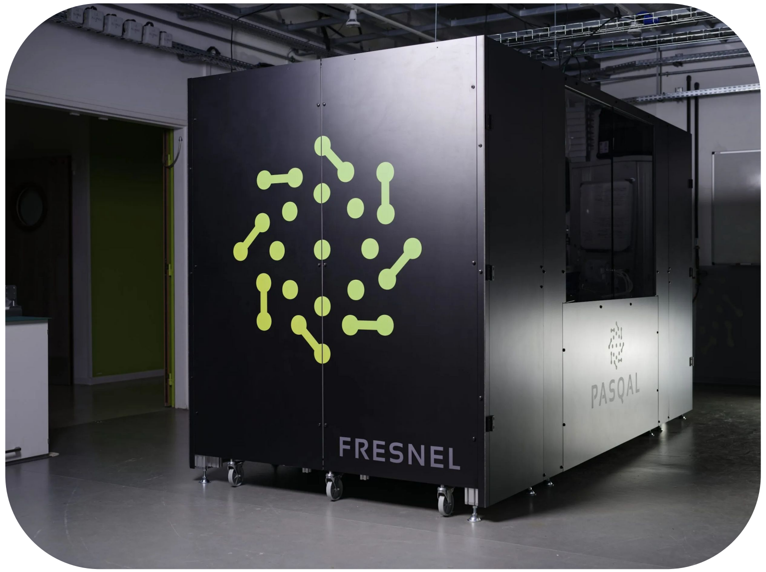
Hybrid quantum-classical algorithms



Leonardo @ CINECA
Supercomputer
3500 CPU, 14000 GPU

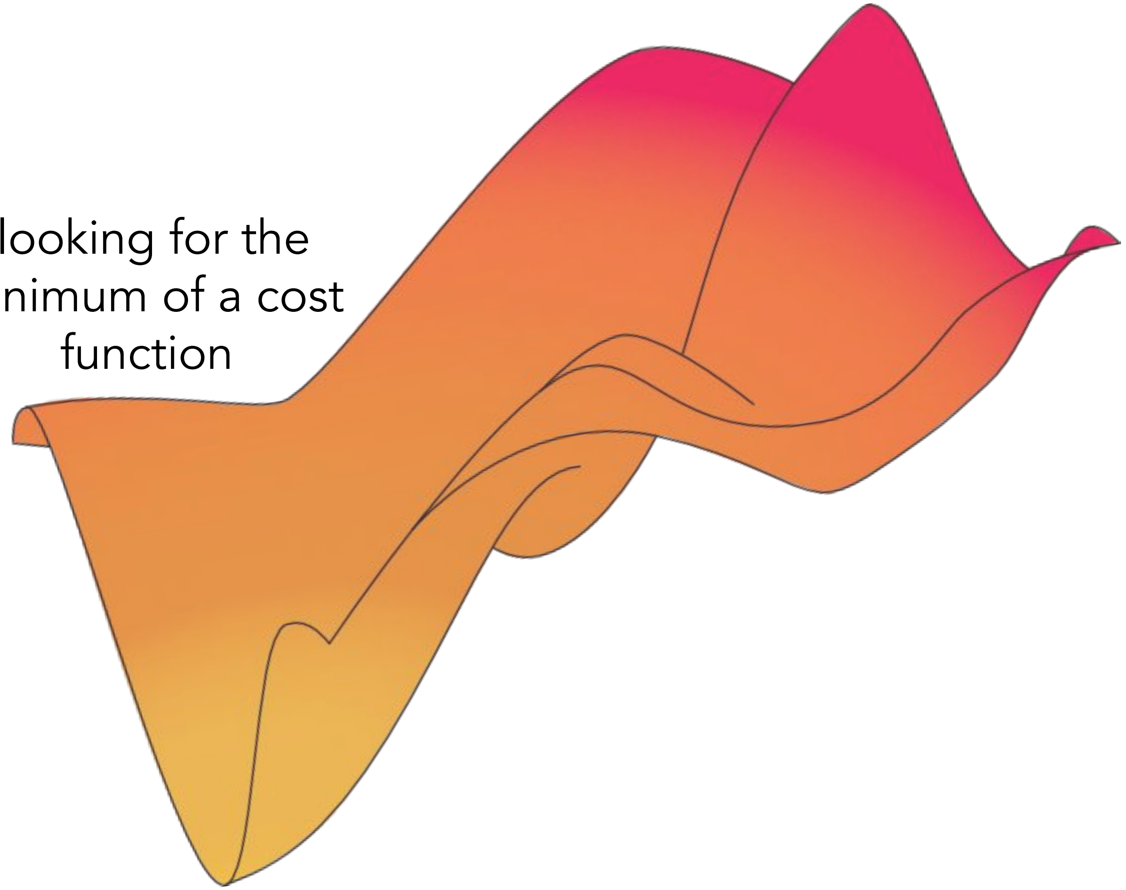
Input parameters

Quantum Computer output



Pasqal (neutral atoms)
300 qubits

Optimization problems



looking for the minimum of a cost function

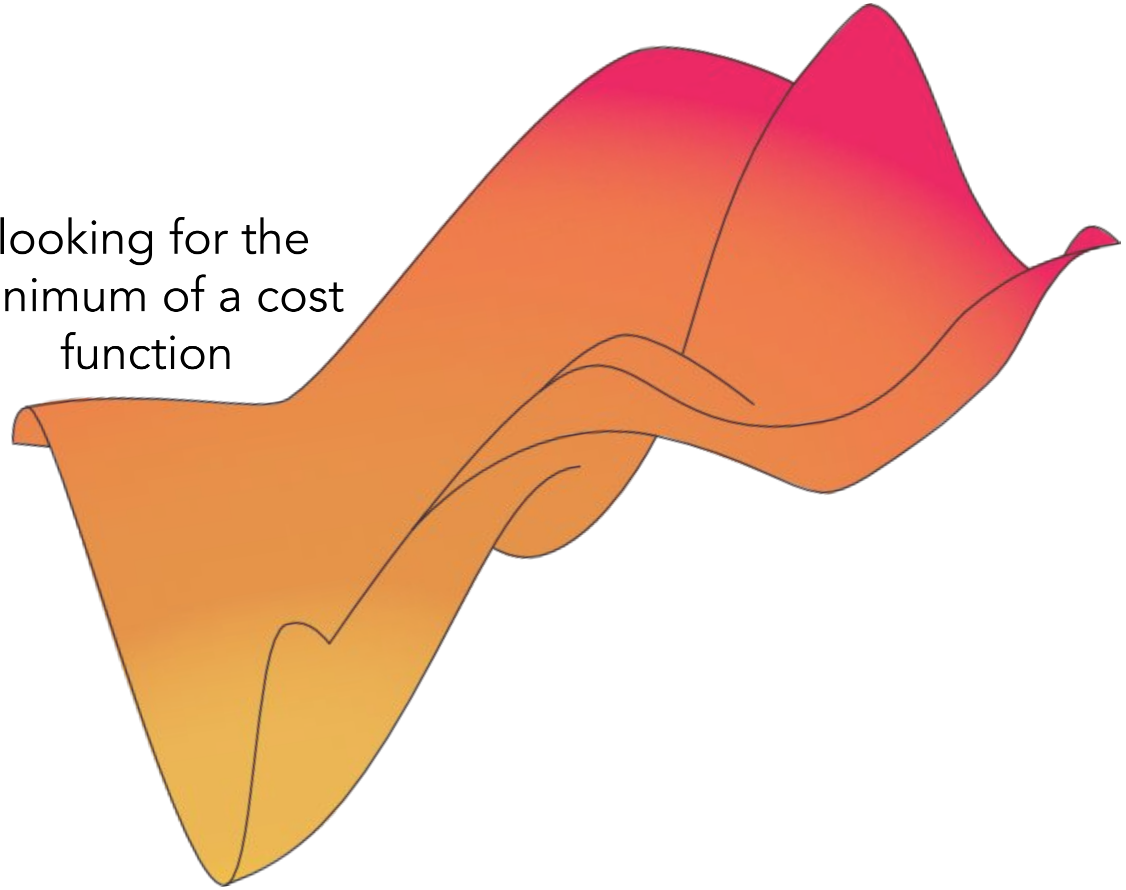
Optimization problems

Earth Observation

Combinatorial optimization problems

(QAOA, quantum annealing, …)

looking for the minimum of a cost function



Traffic

Portfolio optimization

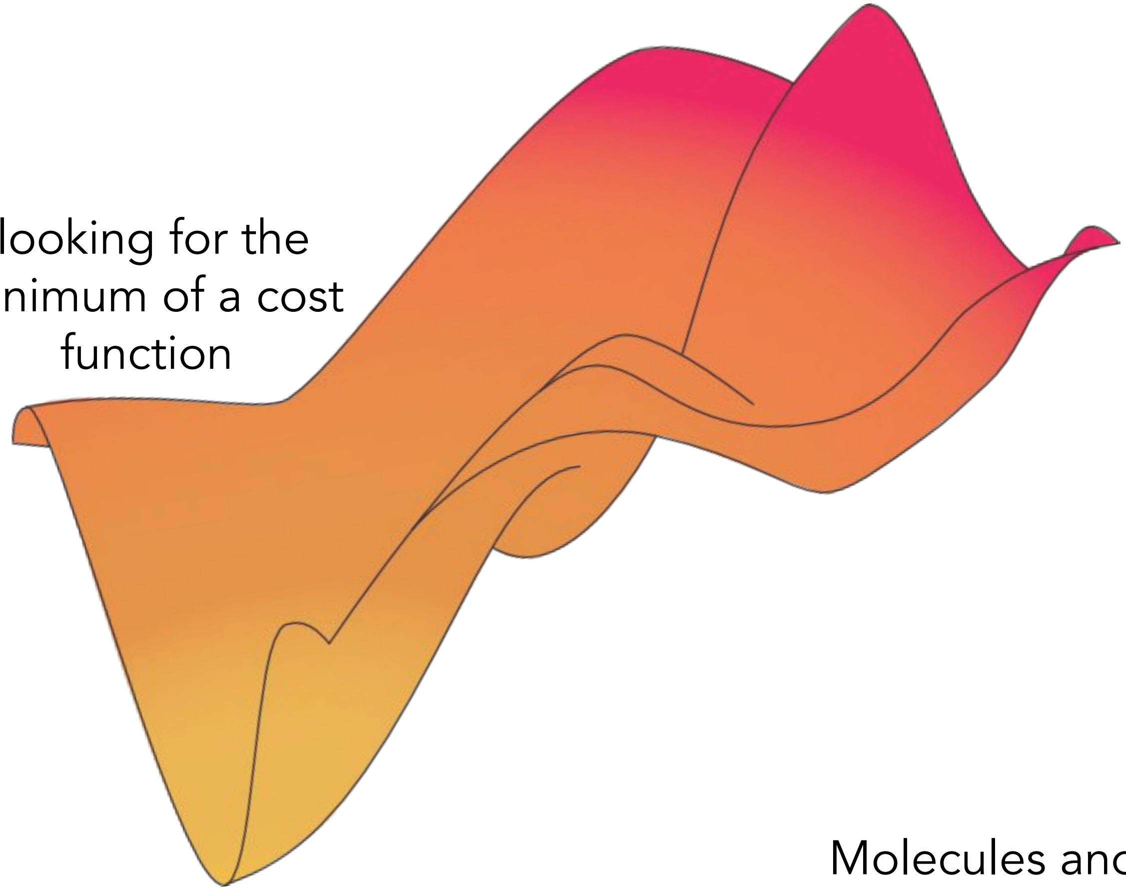
Optimization problems

Earth Observation

Combinatorial optimization problems

(QAOA, quantum annealing, …)

looking for the minimum of a cost function

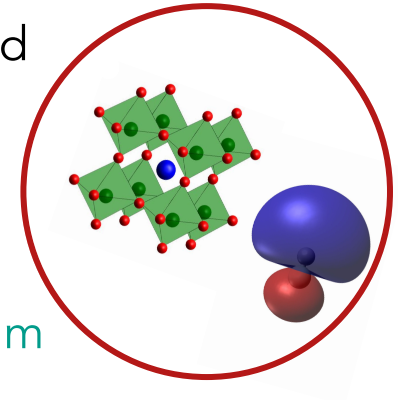


Machine Learning

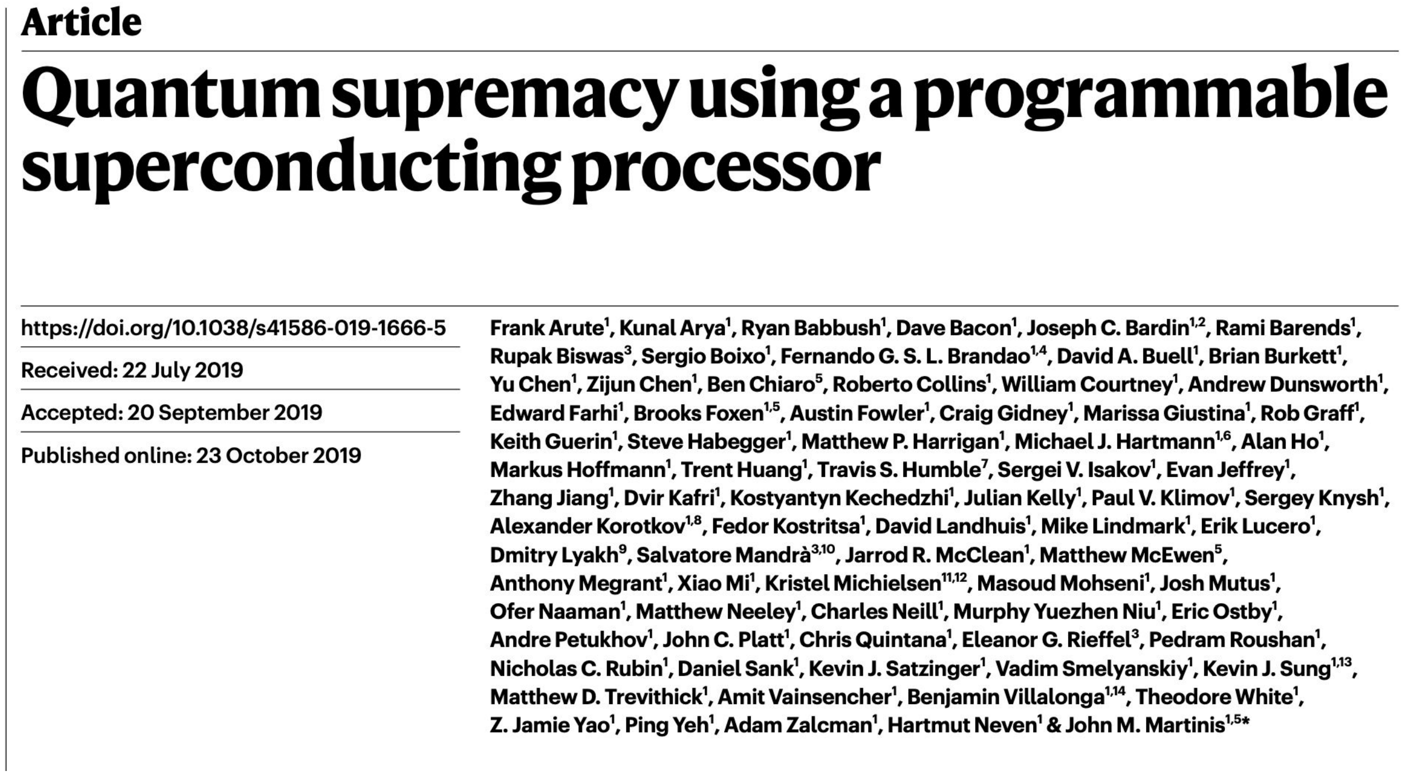
Traffic

Portfolio optimization

Molecules and Materials



(VQE, quantum deflation, …)



Article

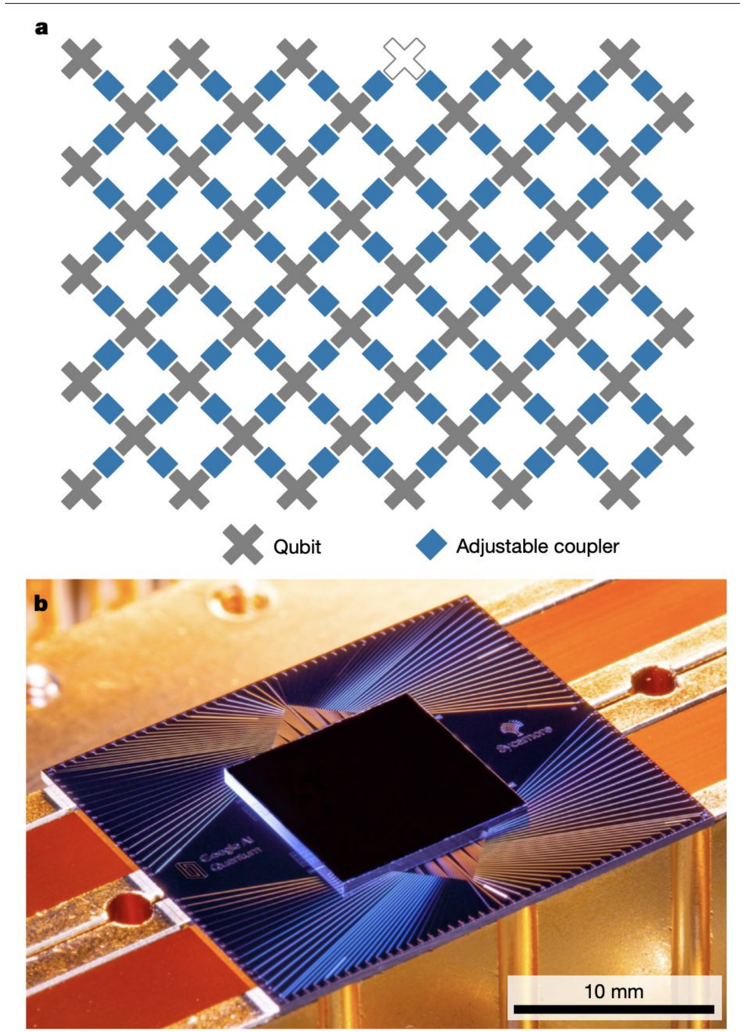
Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5

Received: 22 July 2019

Accepted: 20 September 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1], Zhang Jiang[1], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[1], Alexander Korotkov[1,8], Fedor Kostritsa[1], David Landhuis[1], Mike Lindmark[1], Erik Lucero[1], Dmitry Lyakh[9], Salvatore Mandrà[3,10], Jarrod R. McClean[1], Matthew McEwen[5], Anthony Megrant[1], Xiao Mi[1], Kristel Michielsen[11,12], Masoud Mohseni[1], Josh Mutus[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Murphy Yuezhen Niu[1], Eric Ostby[1], Andre Petukhov[1], John C. Platt[1], Chris Quintana[1], Eleanor G. Rieffel[3], Pedram Roushan[1], Nicholas C. Rubin[1], Daniel Sank[1], Kevin J. Satzinger[1], Vadim Smelyanskiy[1], Kevin J. Sung[1,13], Matthew D. Trevithick[1], Amit Vainsencher[1], Benjamin Villalonga[1,14], Theodore White[1], Z. Jamie Yao[1], Ping Yeh[1], Adam Zalcman[1], Hartmut Neven[1] & John M. Martinis[1,5]*

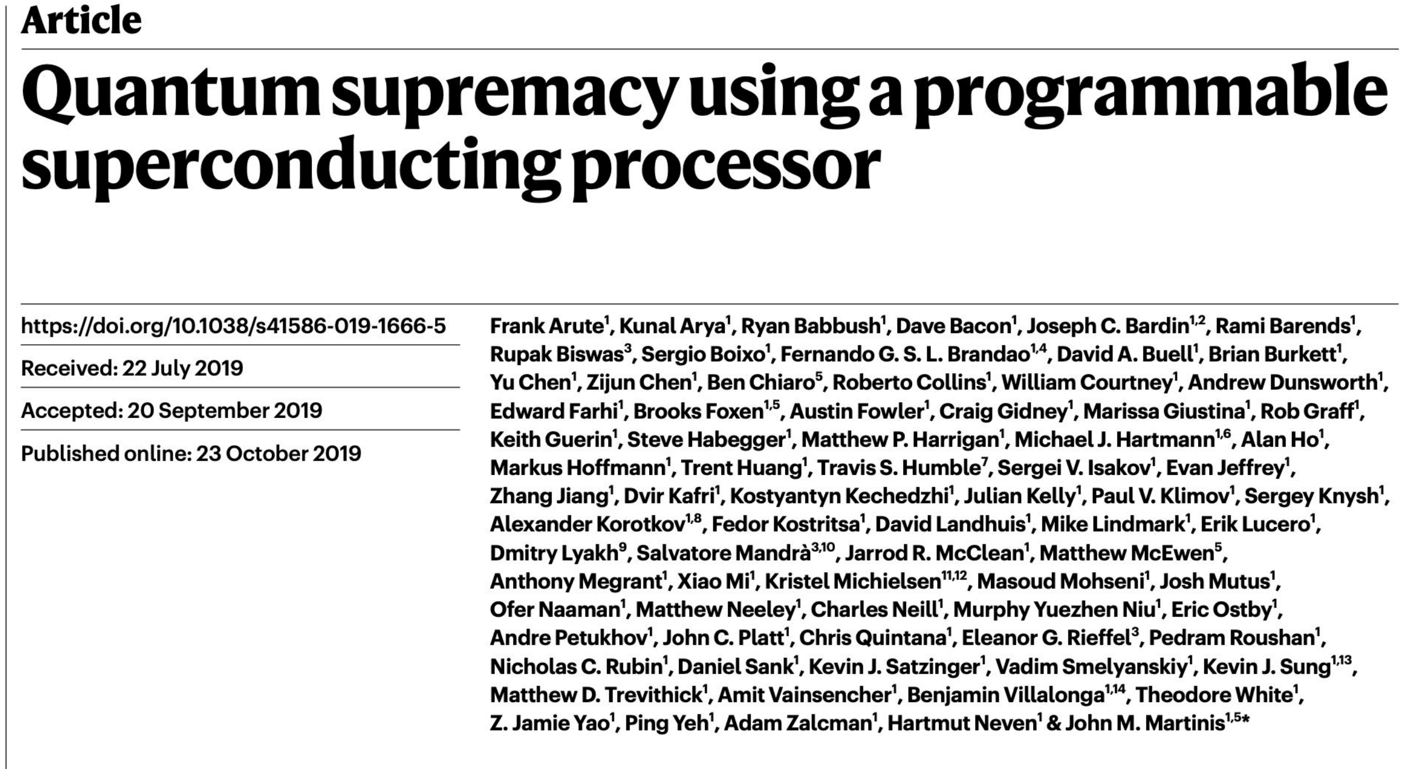


Sycamore, 53 qubits

Quantum supremacy: quantum computer solves a problem faster (with less resources) than a classical computer

Problem: random quantum state generation with a quantum random circuit

!!!! Solution on a classical computer takes 10KY !!!



Article

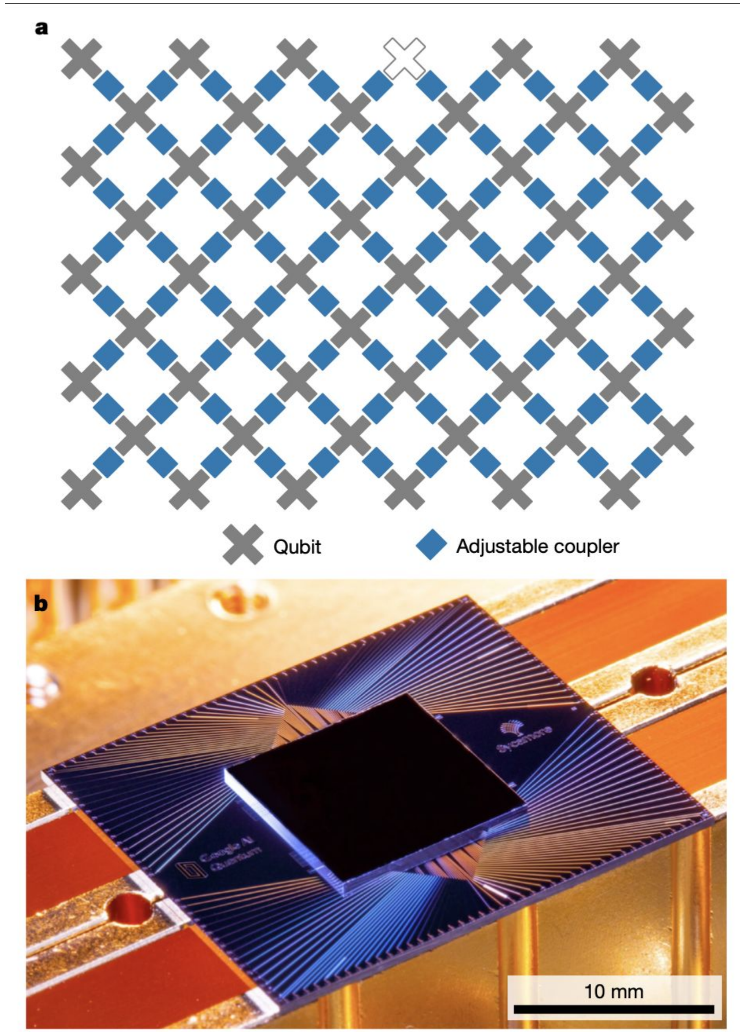
Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5

Received: 22 July 2019

Accepted: 20 September 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1], Zhang Jiang[1], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[1], Alexander Korotkov[1,8], Fedor Kostritsa[1], David Landhuis[1], Mike Lindmark[1], Erik Lucero[1], Dmitry Lyakh[9], Salvatore Mandrà[3,10], Jarrod R. McClean[1], Matthew McEwen[5], Anthony Megrant[1], Xiao Mi[1], Kristel Michielsen[11,12], Masoud Mohseni[1], Josh Mutus[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Murphy Yuezhen Niu[1], Eric Ostby[1], Andre Petukhov[1], John C. Platt[1], Chris Quintana[1], Eleanor G. Rieffel[3], Pedram Roushan[1], Nicholas C. Rubin[1], Daniel Sank[1], Kevin J. Satzinger[1], Vadim Smelyanskiy[1], Kevin J. Sung[1,13], Matthew D. Trevithick[1], Amit Vainsencher[1], Benjamin Villalonga[1,14], Theodore White[1], Z. Jamie Yao[1], Ping Yeh[1], Adam Zalcman[1], Hartmut Neven[1] & John M. Martinis[1,5]*



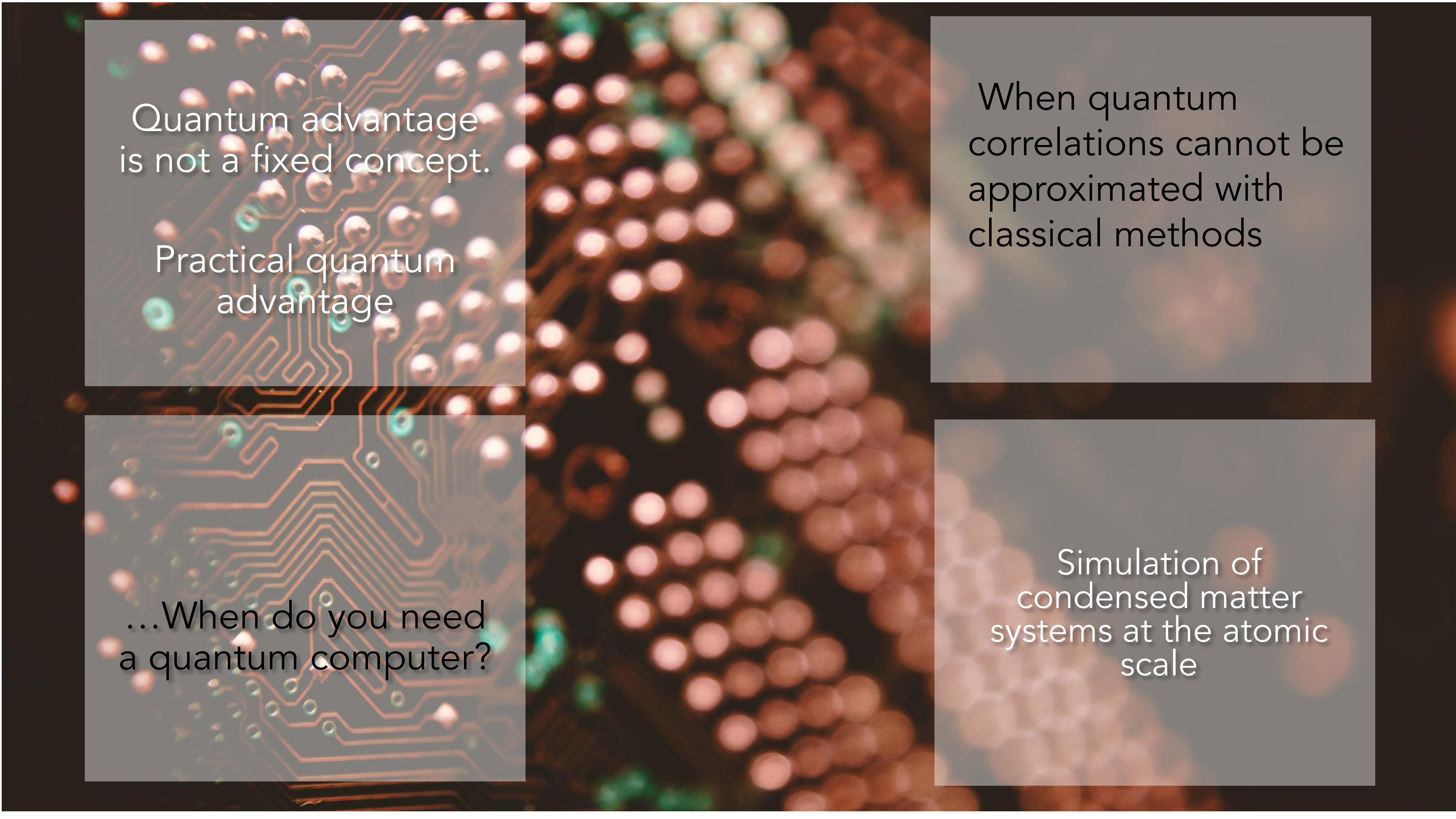
Sycamore, 53 qubits

Quantum supremacy: quantum computer solves a problem faster (with less resources) than a classical computer

Problem: random quantum state generation with a quantum random circuit ☐ Not very useful

!!!! Solution on a classical computer takes 10KY !!!

By approximating quantum correlations, one can simulate 'a faithful' Google experiment on a laptop!



Quantum advantage is not a fixed concept.

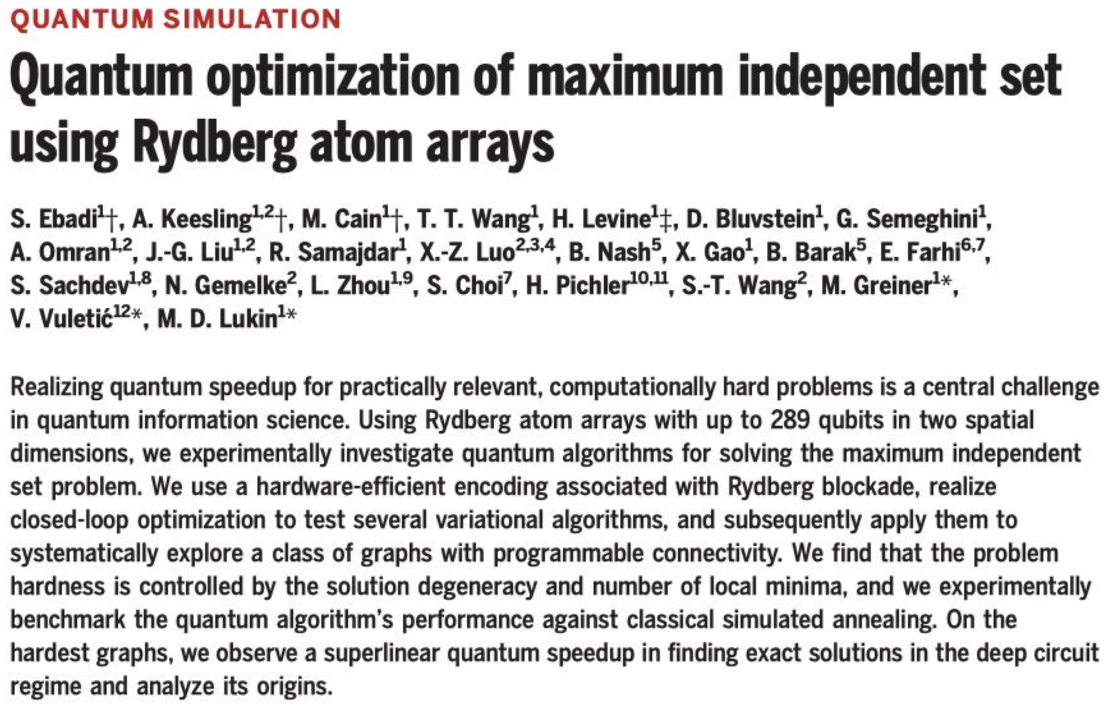
Practical quantum advantage

When quantum correlations cannot be approximated with classical methods

…When do you need a quantum computer?

Simulation of condensed matter systems at the atomic scale

Other examples of quantum advantage

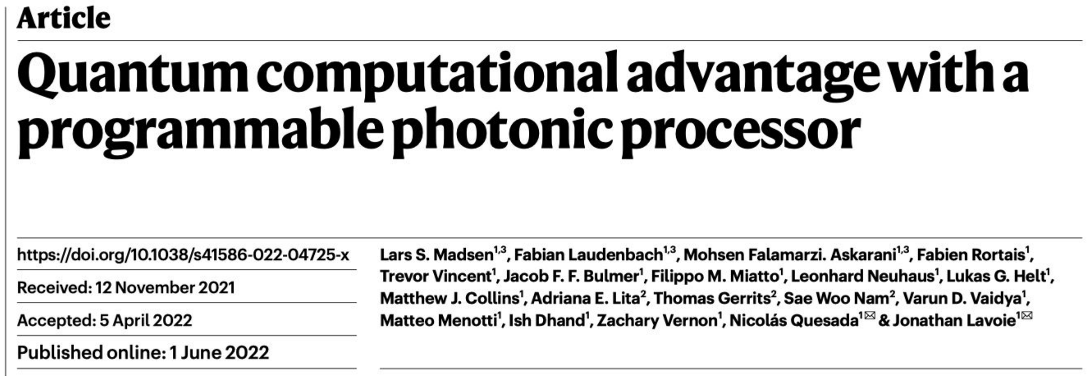


QUANTUM SIMULATION

Quantum optimization of maximum independent set using Rydberg atom arrays

S. Ebadi[1]†, A. Keesling[1,2]†, M. Cain[1]†, T. T. Wang[1], H. Levine[1]‡, D. Bluvstein[1], G. Semeghini[1], A. Omran[1,2], J.-G. Liu[1,2], R. Samajdar[1], X.-Z. Luo[2,3,4], B. Nash[5], X. Gao[1], B. Barak[5], E. Farhi[6,7], S. Sachdev[1,8], N. Gemelke[2], L. Zhou[1,9], S. Choi[7], H. Pichler[10,11], S.-T. Wang[2], M. Greiner[1]*, V. Vuletić[12]*, M. D. Lukin[1]*

Realizing quantum speedup for practically relevant, computationally hard problems is a central challenge in quantum information science. Using Rydberg atom arrays with up to 289 qubits in two spatial dimensions, we experimentally investigate quantum algorithms for solving the maximum independent set problem. We use a hardware-efficient encoding associated with Rydberg blockade, realize closed-loop optimization to test several variational algorithms, and subsequently apply them to systematically explore a class of graphs with programmable connectivity. We find that the problem hardness is controlled by the solution degeneracy and number of local minima, and we experimentally benchmark the quantum algorithm's performance against classical simulated annealing. On the hardest graphs, we observe a superlinear quantum speedup in finding exact solutions in the deep circuit regime and analyze its origins.



Article

Quantum computational advantage with a programmable photonic processor

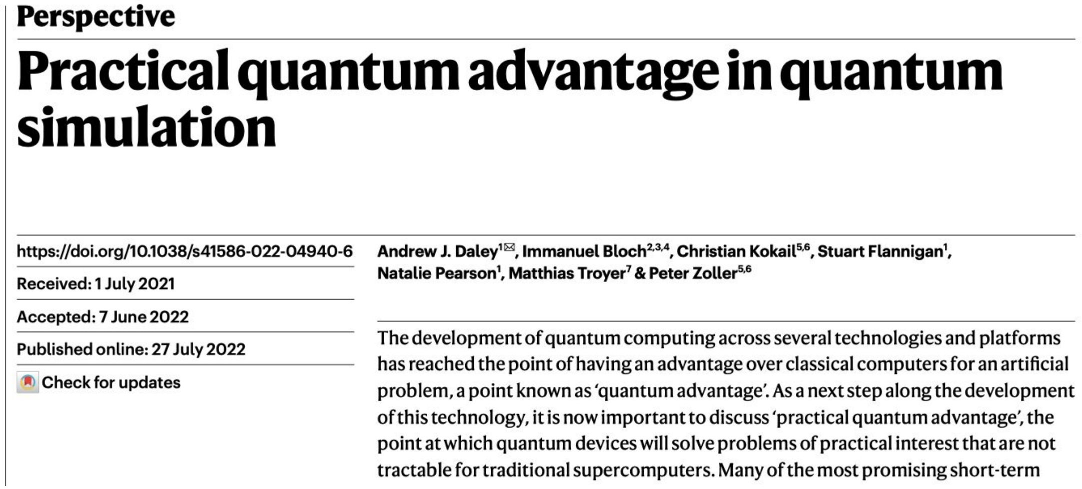
https://doi.org/10.1038/s41586-022-04725-x

Received: 12 November 2021

Accepted: 5 April 2022

Published online: 1 June 2022

Lars S. Madsen[1,3], Fabian Laudenbach[1,3], Mohsen Falamarzi. Askarani[1,3], Fabien Rortais[1], Trevor Vincent[1], Jacob F. F. Bulmer[1], Filippo M. Miatto[1], Leonhard Neuhaus[1], Lukas G. Helt[1], Matthew J. Collins[1], Adriana E. Lita[2], Thomas Gerrits[2], Sae Woo Nam[2], Varun D. Vaidya[1], Matteo Menotti[1], Ish Dhand[1], Zachary Vernon[1], Nicolás Quesada[1]✉ & Jonathan Lavoie[1]✉



Perspective

Practical quantum advantage in quantum simulation

https://doi.org/10.1038/s41586-022-04940-6

Received: 1 July 2021

Accepted: 7 June 2022

Published online: 27 July 2022

Check for updates

Andrew J. Daley[1]✉, Immanuel Bloch[2,3,4], Christian Kokail[5,6], Stuart Flannigan[1], Natalie Pearson[1], Matthias Troyer[7] & Peter Zoller[5,6]

The development of quantum computing across several technologies and platforms has reached the point of having an advantage over classical computers for an artificial problem, a point known as 'quantum advantage'. As a next step along the development of this technology, it is now important to discuss 'practical quantum advantage', the point at which quantum devices will solve problems of practical interest that are not tractable for traditional supercomputers. Many of the most promising short-term

Basics of quantum computation

QUBIT

Fundamental unit of quantum information

|0>,|1>

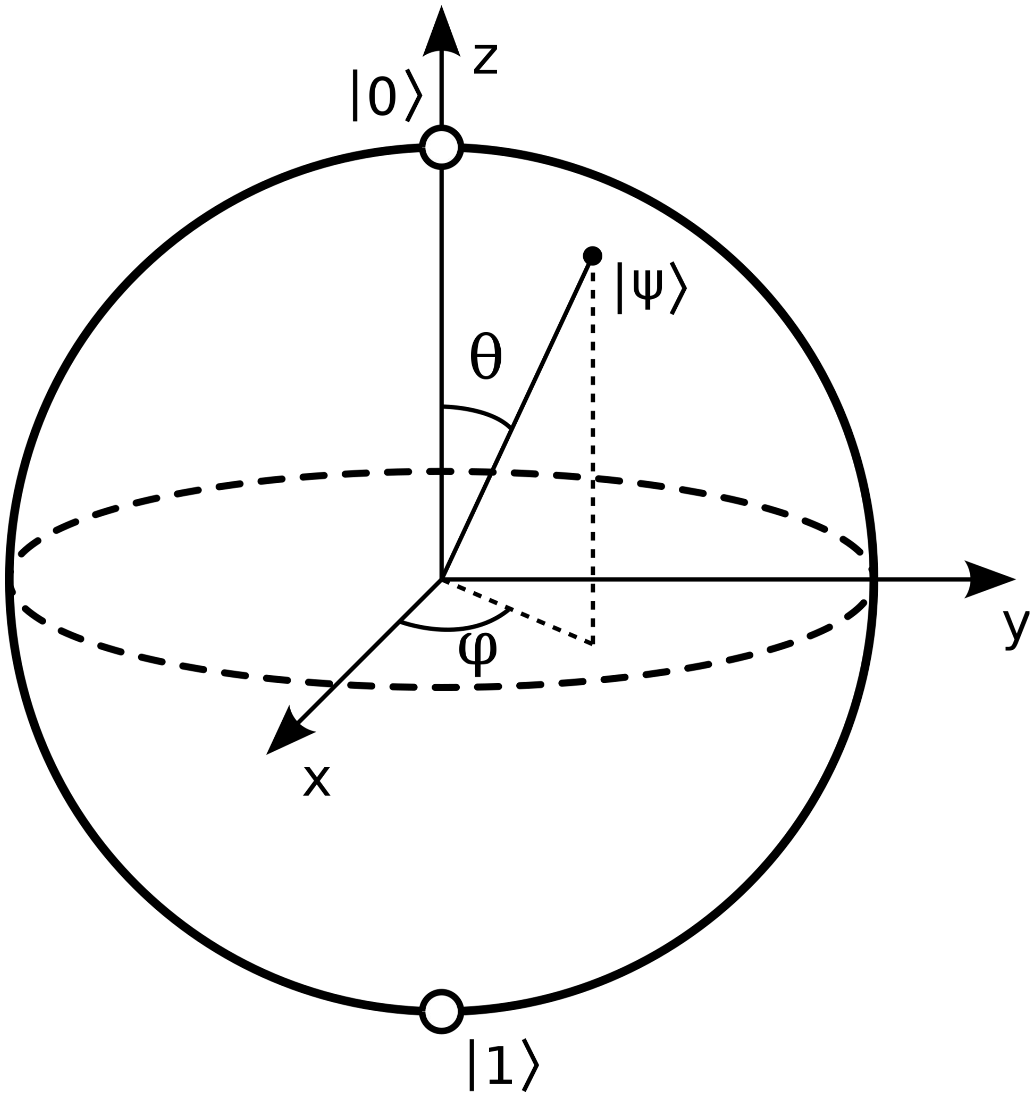
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

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

1 qubit $\xrightarrow[\text{measurement}]{}$ 1 bit of classical information

2 qubit

- Two qubit states $|00\rangle, |01\rangle, |10\rangle, |11\rangle$
- superposition $|\Psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$



Single qubits gates

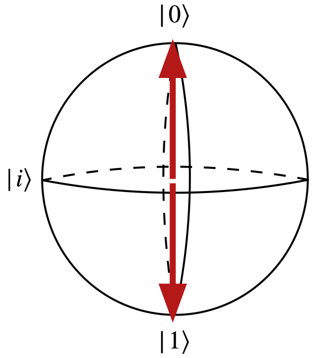
Two-qubit gates

NOT
(X)

input *output*

$$|0\rangle \rightarrow |1\rangle$$

$$|1\rangle \rightarrow |0\rangle$$



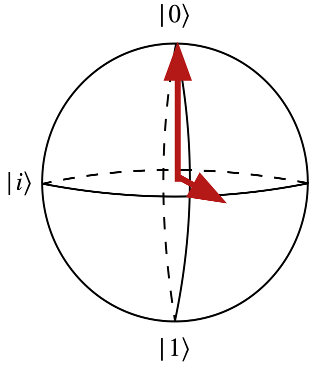
Hadamard
(H)

input *output*

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

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

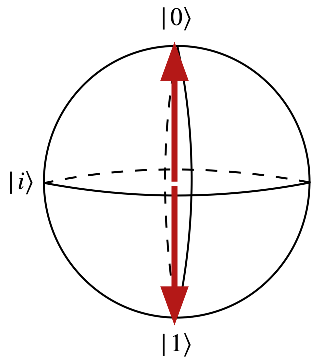
superposition



Single qubits gates

NOT (X)

input	*output*
$|0\rangle$	$\rightarrow |1\rangle$
$|1\rangle$	$\rightarrow |0\rangle$



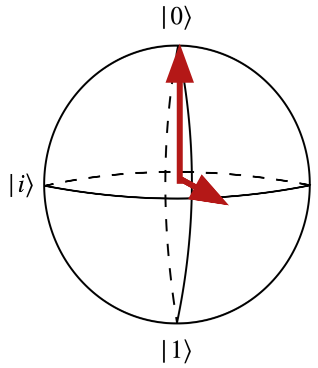
Hadamard (H)

input *output*

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

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

sovrapposizione



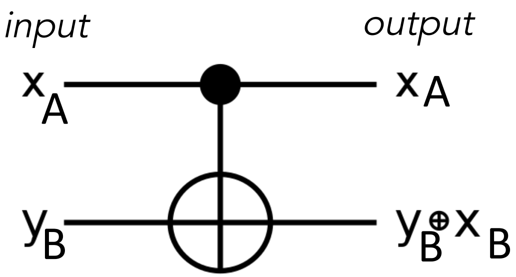
Two-qubit gates

CNOT

input	*output*
$|0_A 0_B\rangle$	$\rightarrow |0_A 0_B\rangle$
$|0_A 1_B\rangle$	$\rightarrow |0_A 1_B\rangle$
$|1_A 0_B\rangle$	$\rightarrow |1_A 1_B\rangle$
$|1_A 1_B\rangle$	$\rightarrow |1_A 0_B\rangle$

B is controlled by A

Quantum correlations



Universal set of gates: any algorithm can be decomposed as a sequence of ({CNOT, single qubit gate})

Reversibility’: can always go back to the input from the output

QUANTUM COMPUTER

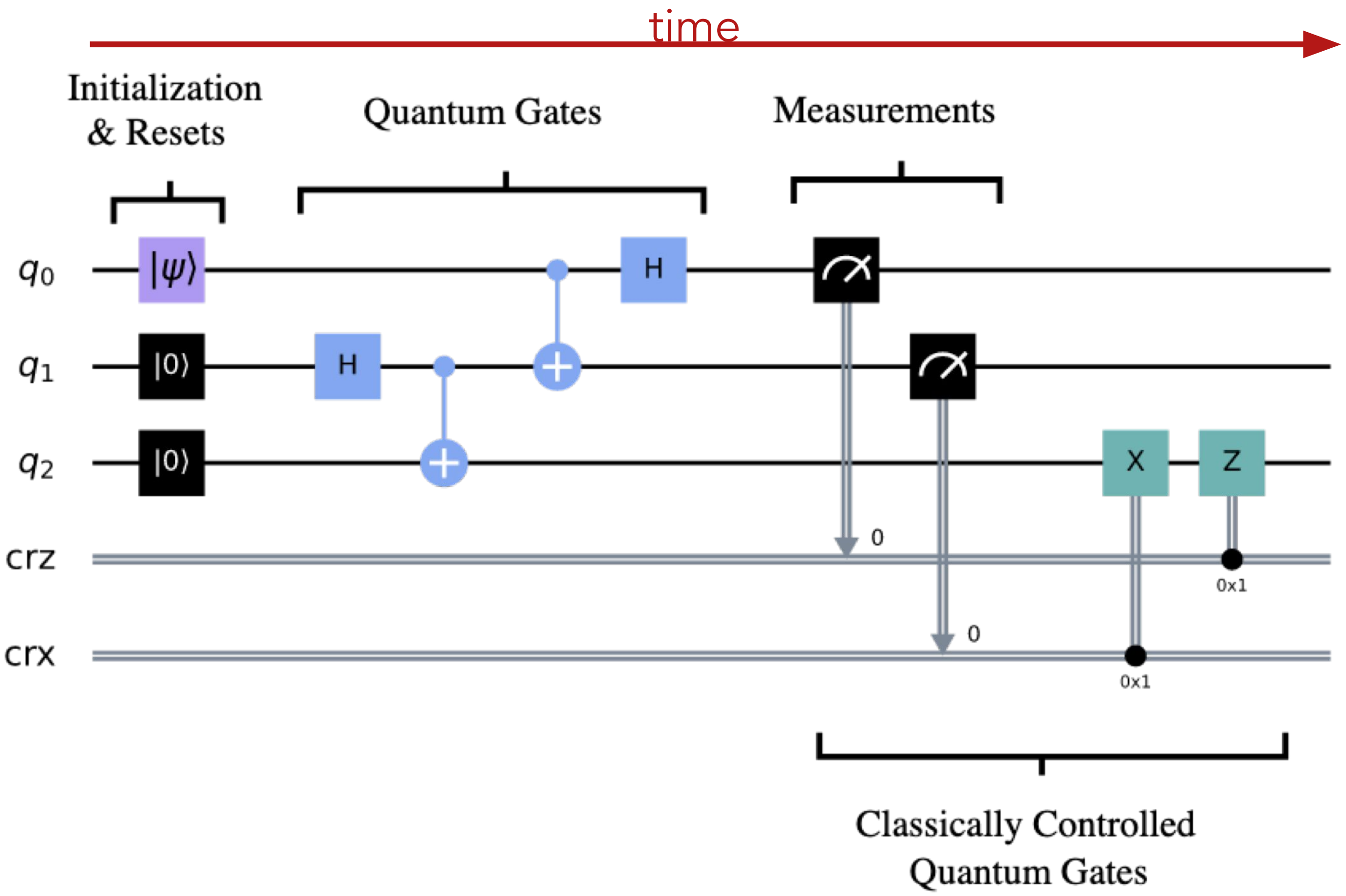
- WHAT?

A quantum computer is a physical system composed of many qubits, whose dynamics is controlled;

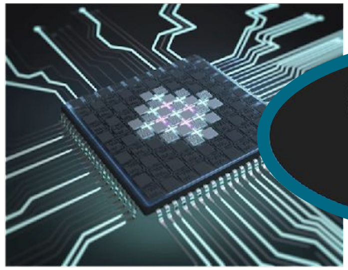
- HOW?

It processes information via logical operations while exploiting the laws of quantum mechanics

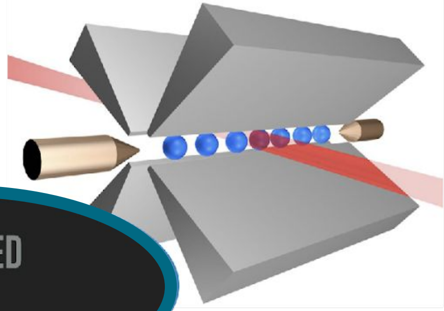
QUANTUM CIRCUIT



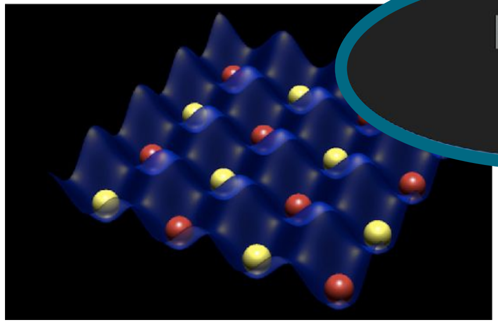
Physical systems



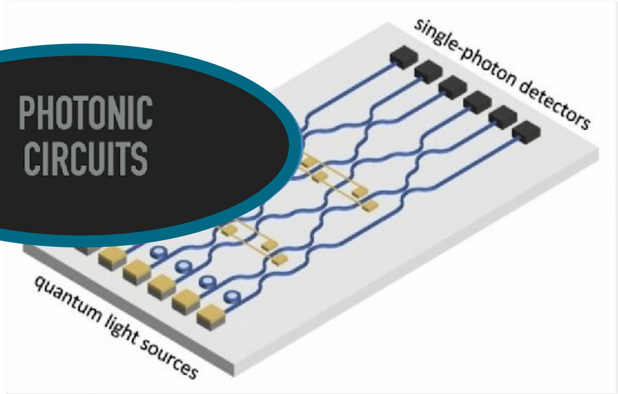
SUPERCONDUCTING CIRCUITS



TRAPPED IONS

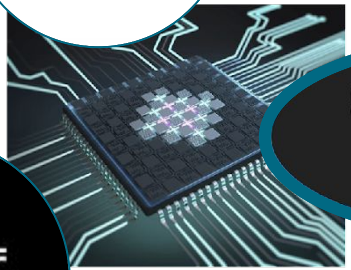


NEUTRAL ATOMS



PHOTONIC CIRCUITS

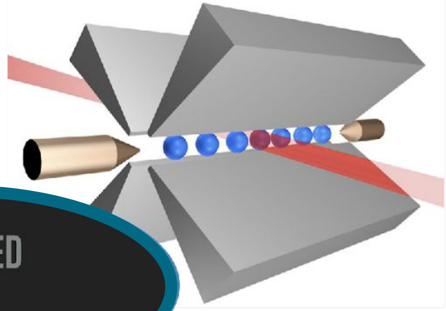
Physical systems



SUPERCONDUCTING CIRCUITS

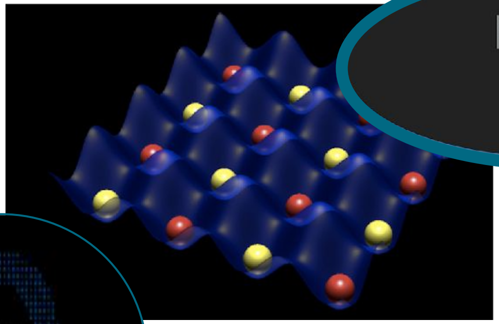
Google AI

IBM



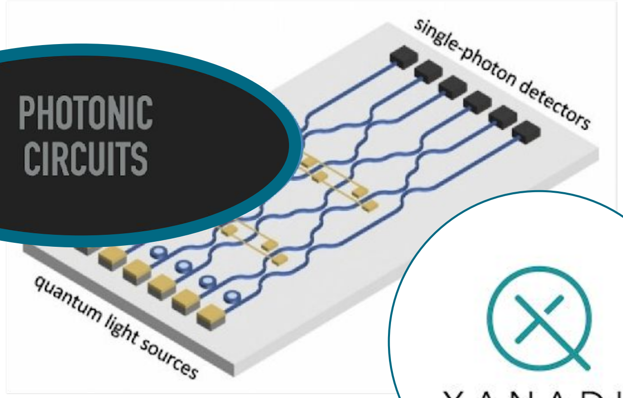
TRAPPED IONS

IONQ



NEUTRAL ATOMS

QuEra



PHOTONIC CIRCUITS

XANADU

QUANTUM
COMPUTING
AND
SIMULATION
CENTER

Incontri introduttivi al Quantum Computing

14/03/2023, h. 17:00

Calcolatori e simulatori quantistici nella NISQ era: cosa sono e cosa possono fare

Ilaria Siloi (Unipd)

21/03/2023, h. 17:00

Introduzione all'emulatore di calcolatore quantistico HPC “Quantum Matcha Tea”

Marco Ballarin (Unipd)

28/03/2023, h. 17:00

Introduzione alle macchine Dwave

Gabriella Bettonte (CINECA)

04/04/2023, h. 17:00

Introduzione alle macchine PASQAL

Riccardo Mengoni (CINECA)

11/04/2023, h. 17:00

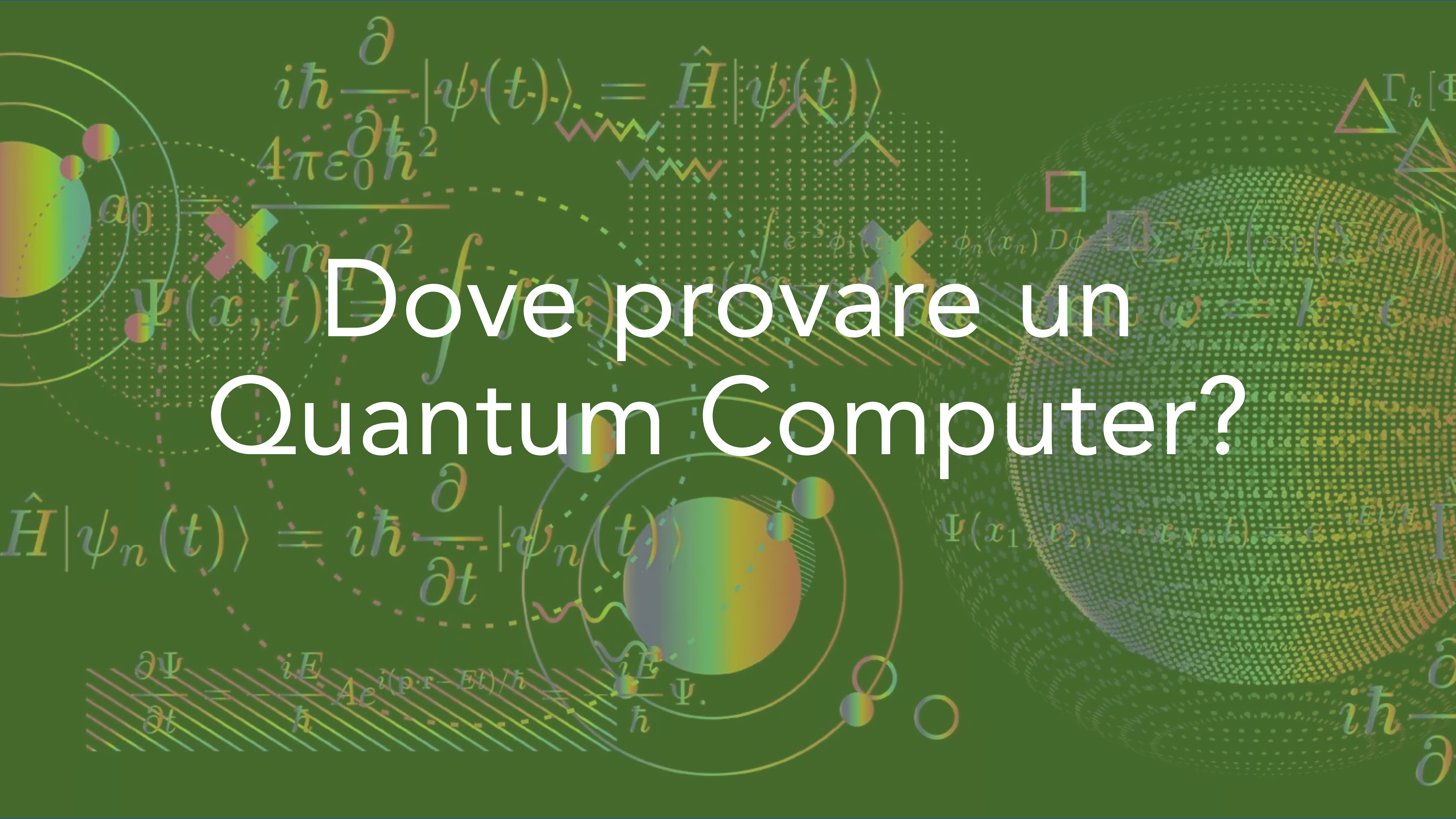
Introduzione alle macchine QuERA Computing

Tommaso Macrì (QuERA)

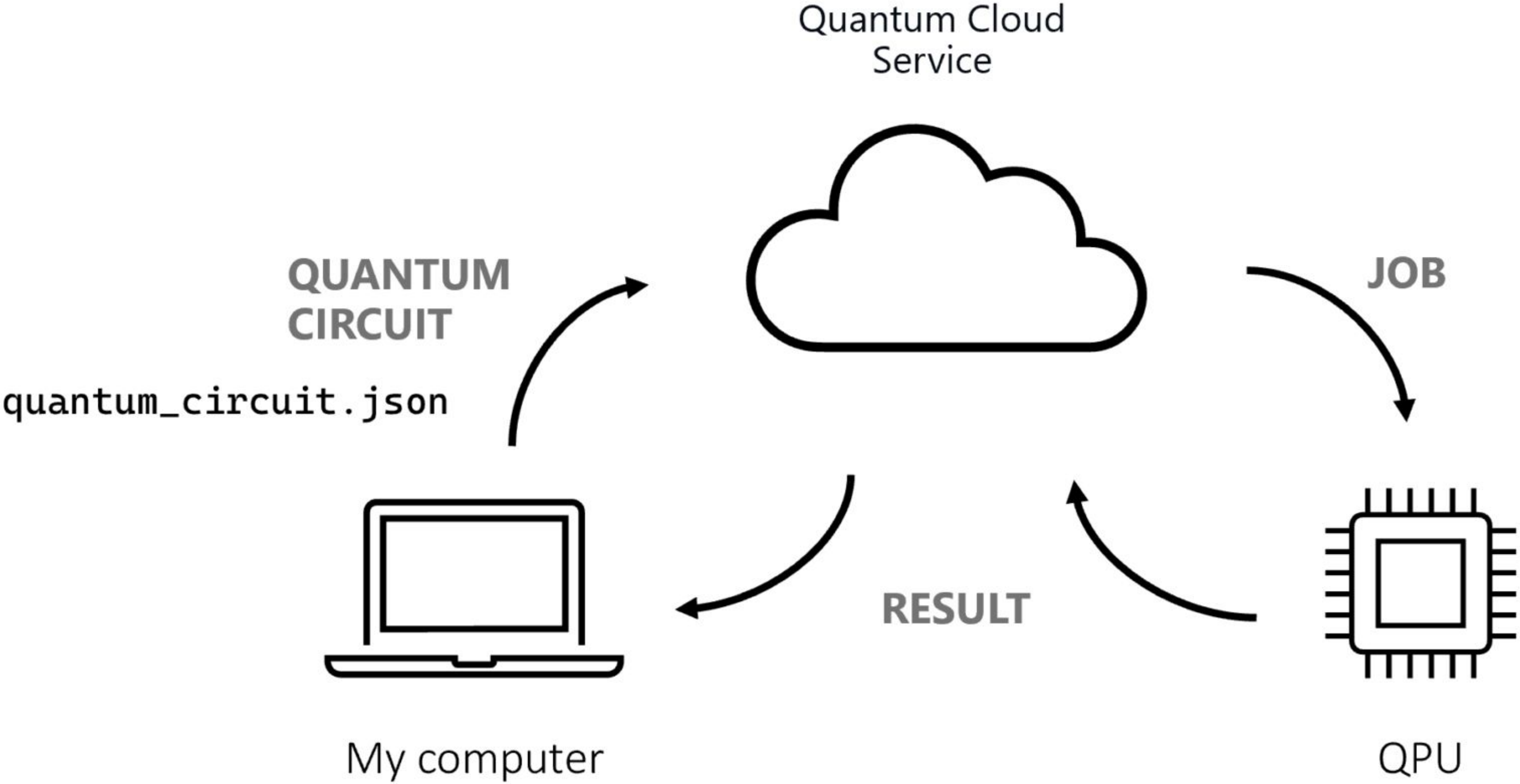
Tutte le lezioni saranno su zoom (al link: **https://unipd.link/QCSC-Lessons**),
registrate e rese disponibili sul sito **qcsc.dfa.unipd.it**

Partners

Thank you !



Dove provare un Quantum Computer?



Quantum Cloud
Service

QUANTUM
CIRCUIT

`quantum_circuit.json`

JOB

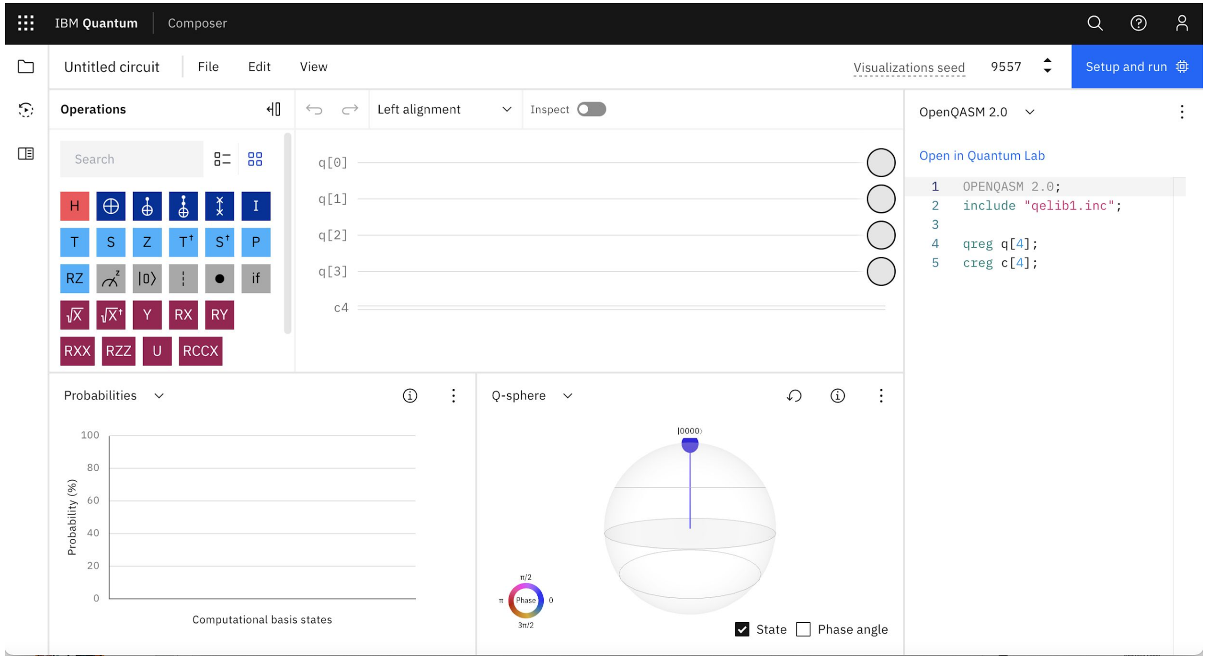
RESULT

My computer

QPU

https://quantum-computing.ibm.com

Accesso gratuito a tempo macchina su quantum computer



Untitled circuit

Visualizations seed 9557

OpenQASM 2.0

```
OPENQASM 2.0;
include "qelib1.inc";

qreg q[4];
creg c[4];
```

WORLD QUANTUM DAY

IN PADOVA

14 APRILE 2023
CENTRO UNIVERSITARIO
VIA ZABARELLA 82

EDIZIONE 1

PROGRAMMA

DALLE 14:00
FROM
ALLE 19:30
TO

- GIOCHI DA TAVOLO
  BOARD GAMES
- VIDEOGIOCHI
  COMPUTER GAMES
- LABORATORIO D'ARTE
  ART LAB

...AND MORE

INGRESSO LIBERO
FREE ENTRANCE

JOIN THE QUANTUM SIDE!

Dipartimento di Fisica e Astronomia Galileo Galilei
UNIVERSITÀ DEGLI STUDI DI PADOVA

QUANTUM COMPUTING AND SIMULATION CENTER

WQD APRIL 14

Grazie!

Bit e' una variabile binaria
unita' elementare di informazione classica

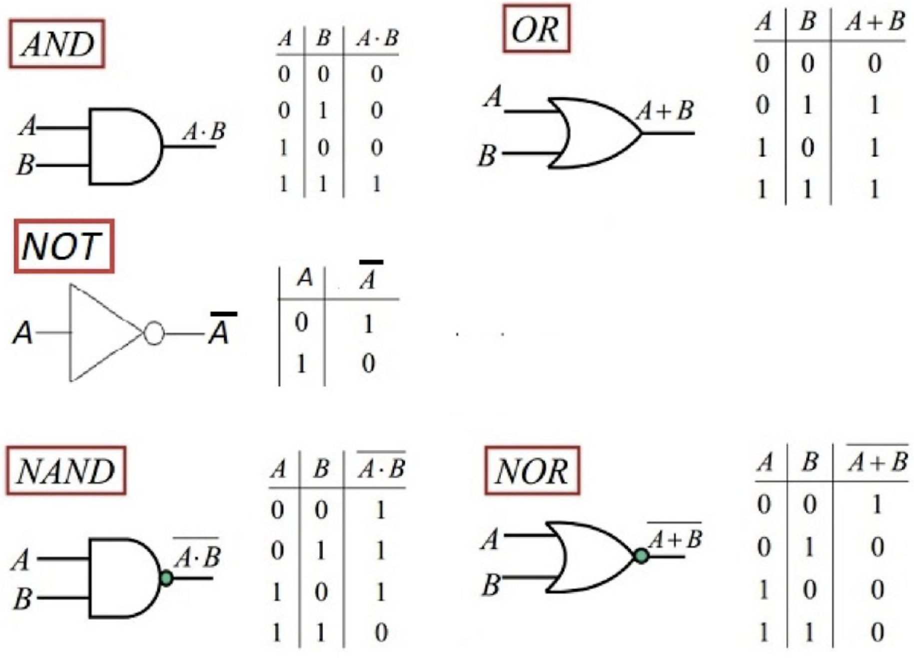
0 1

Rapresentazione decimale VS binaria

$(11)_d = 1 \times 10^1 + 1 \times 10^0 = (8+2+1)_d$
$= 1 \times 2^3 + 0\hat{}2^2 + 1 \times 2^1 + 1 \times 2^0$
$(1011)_b$

$(3.14)_d = (11.001000111\ldots)_b$

Porte logiche (gate) operano sui bits attraverso la logica Booleana.



A	B	A·B
0	0	0
0	1	0
1	0	0
1	1	1

A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

A	$\bar{A}$
0	1
1	0

A	B	$\overline{A \cdot B}$
0	0	1
0	1	1
1	0	1
1	1	0

A	B	$\overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

= Le porte logiche sono componenti fisiche che usano i transistor per operare gli switch elettronici quando una certa condizione e' verificata.

Operazione logica: $f: \{0,1\}^n$□ $\{0,1\}^m$

Set universale di gate: ogni calcolo e' scrivibile come una sequenza finite di alcune porte logiche ({AND-OR-FANOUT}, {NAND})

Irreversibilita' (n != m) non sempre dal risultato si torna all'input

“…l’informazione e‘ fisica…“