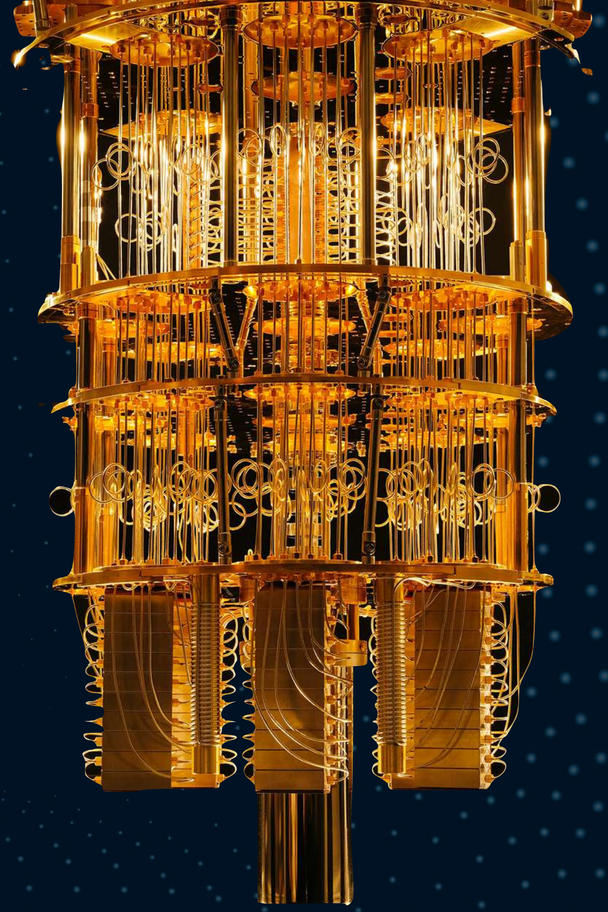
Introduzione alla Computazione Quantistica

come, chi, quando e…perché?



Stefano Mangini

📍Algorithmiq / University of Helsinki

✉️ stefano.mangini@algorithmiq.fi

29 Marzo 2025

IANUA, Università di Genova

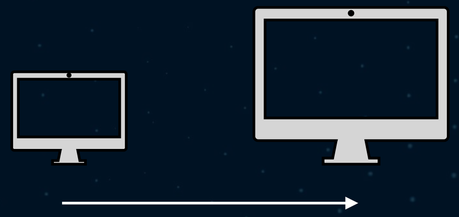
Parte I

Computazione quantistica: cosa e perchè?

(slides, ~1.5h)

Cosa è?

A cosa serve?



Come si fa?

Parte II

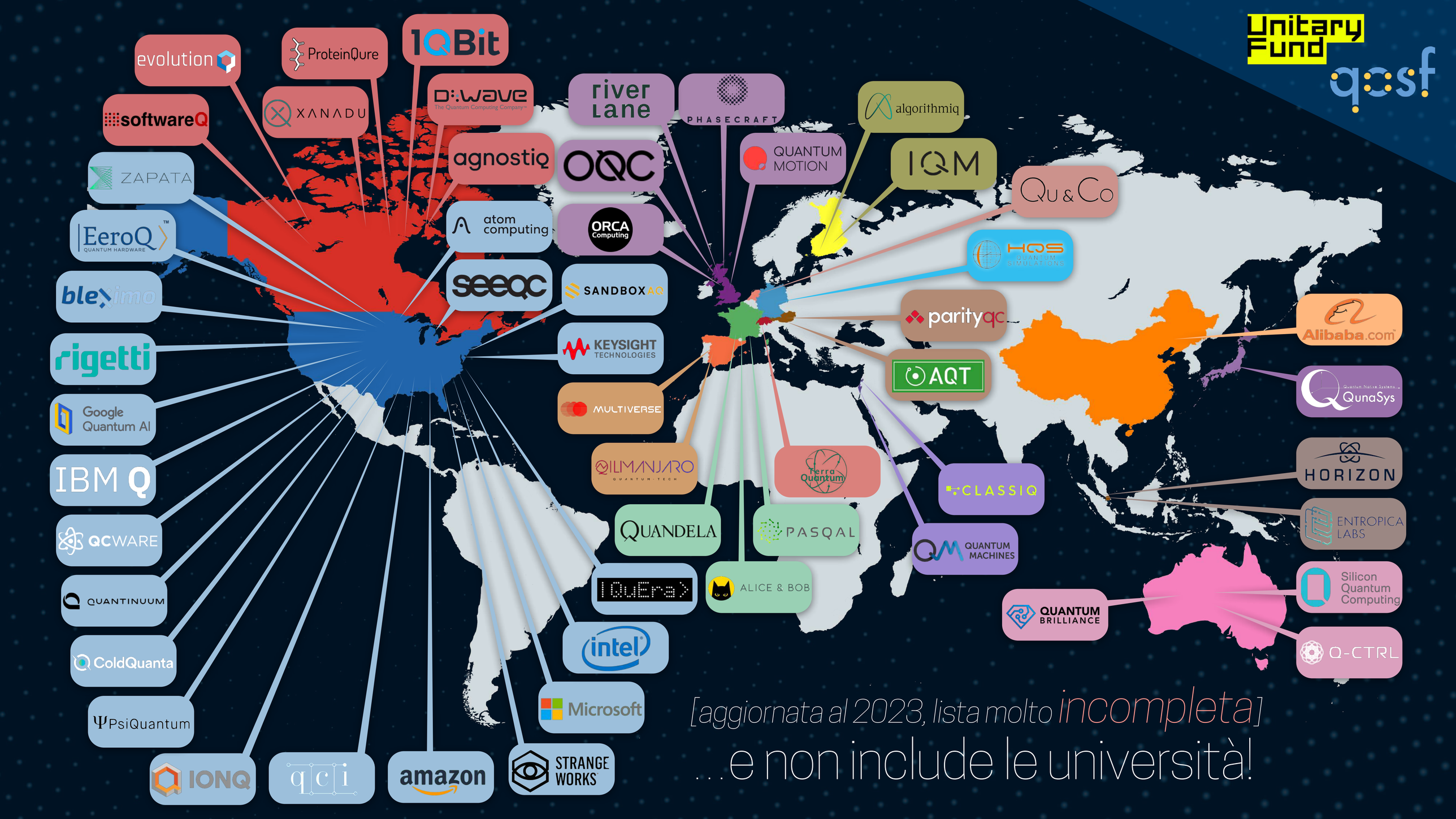
Hands-on: programmiamo un computer quantistico

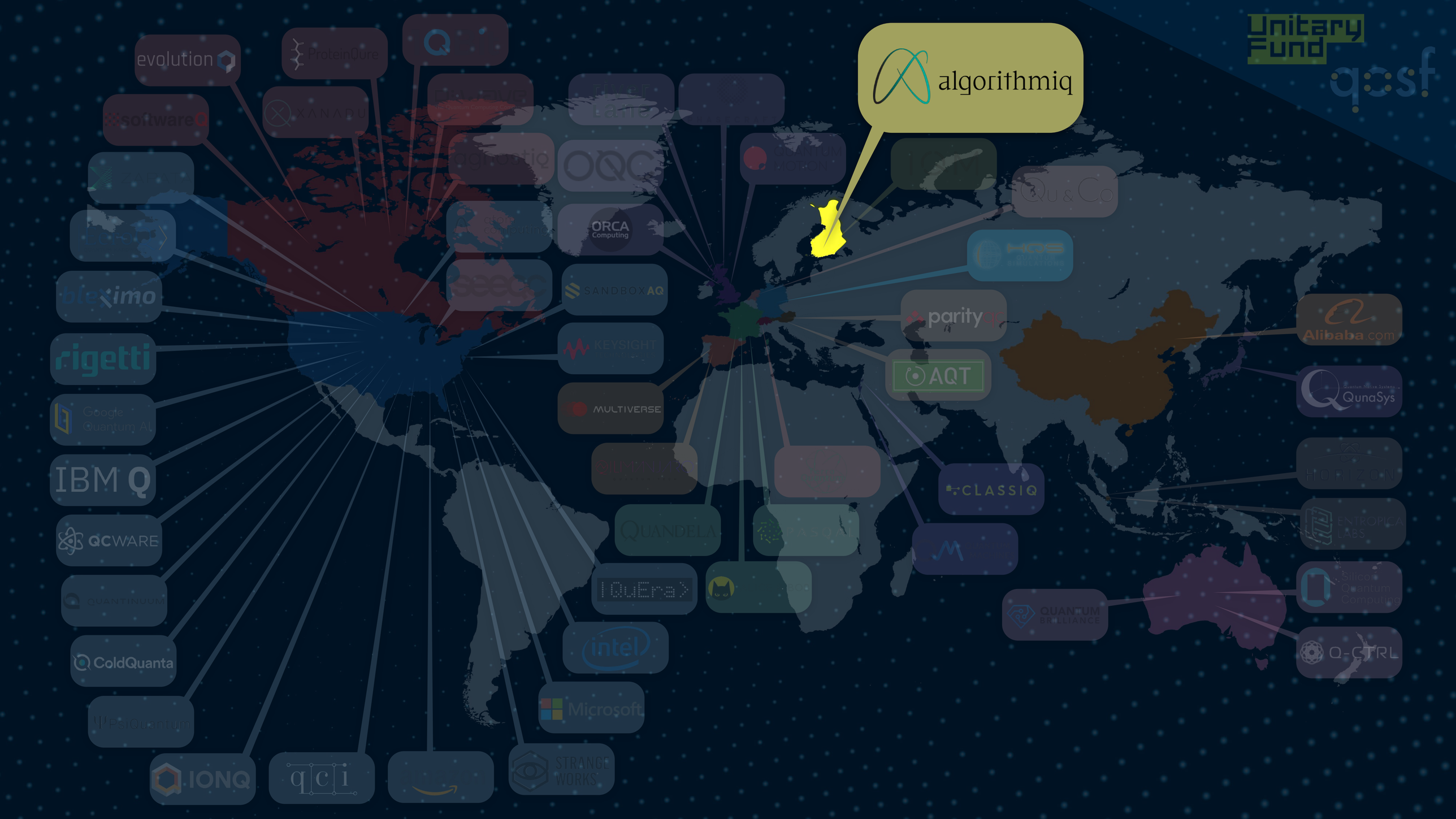
(computer, ~1.5h)

Quantum software

Circuiti quantistici

Argomenti avanzati (rumore)


Unitary Fund
qcsf
evolution
ProteinQure
1QBit
softwareQ
XANADU
D:Wave
The Quantum Computing Company
river Lane
PHASECRAFT
algorithmiq
ZAPATA
agnostiq
OQC
QUANTUM MOTION
IQM
Qu & Co
EeroQ
QUANTUM HARDWARE
atom computing
ORCA Computing
HQS
QUANTUM SIMULATIONS
blexiMo
seeqc
SANDBOX AQ
parityqc
Alibaba.com
rigetti
KEYSIGHT TECHNOLOGIES
AQT
Google Quantum AI
MULTIVERSE
QunaSys
Quantum Native Systems
IBM Q
QILIMANJARO
QUANTUM TECH
Terra Quantum
CLASSIQ
HORIZON
QCWARE
QUANDELA
PASQAL
ENTROPICA LABS
QUANTINUUM
QUANTUM MACHINES
|QuEra>
ALICE & BOB
Silicon Quantum Computing
ColdQuanta
intel
QUANTUM BRILLIANCE
Q-CTRL
ΨPsiQuantum
Microsoft
IONQ
qci
amazon
STRANGE WORKS
[aggiornata al 2023, lista molto incompleta]
...e non include le università!


algorithmiq
Unitary Fund
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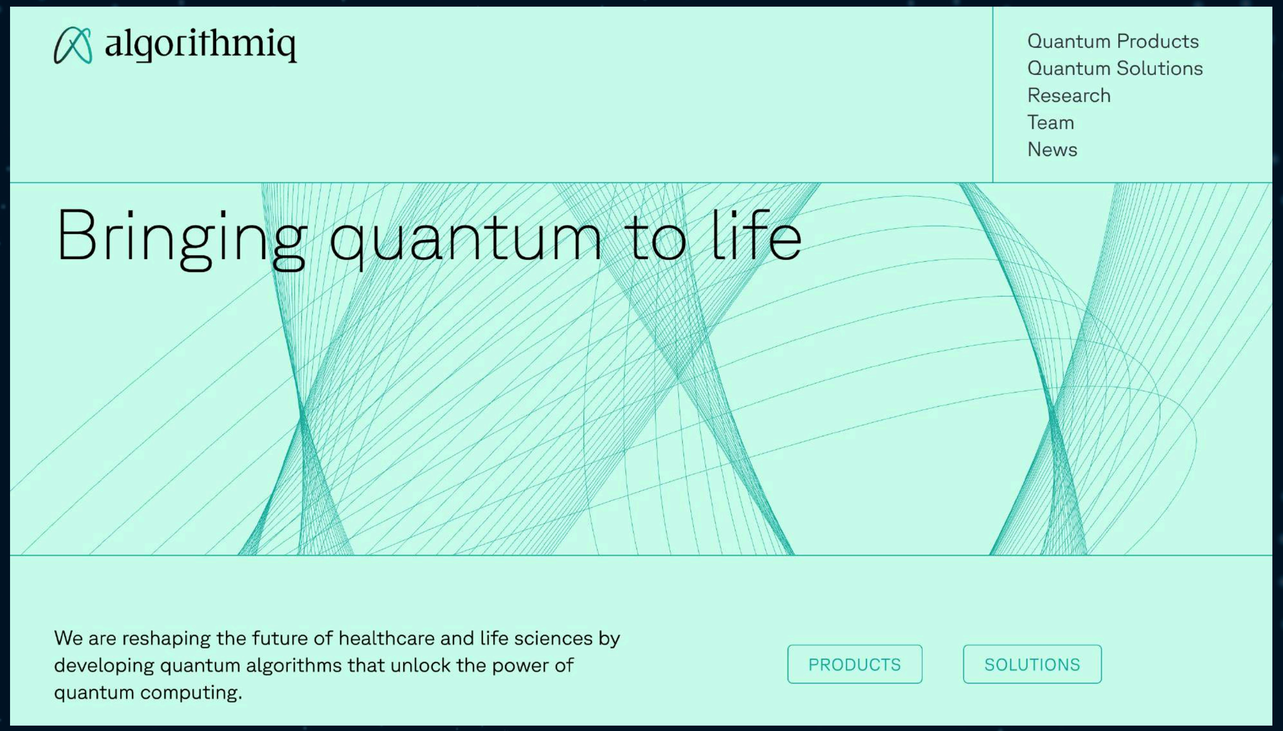
Q-CTRL
bleximo
rigetti
Google Quantum AI
IBM Q
QCWARE
QUANTINUUM
ColdQuanta
PsiQuantum
IONQ
qci
intel
Microsoft
STRANGE WORKS

algorithmiq
in due parole



Quando
Startup (scale up) fondata nel 2020

Cosa
Algoritmi quantistici per applicazion in life sciences (quantum chemistry, drug design, ...)

Come
+80% PhDs in quantum computing/chemistry/...
ricerca, articoli scientifici
brevetti ,software

Chi
+40 dipendenti sparsi per il globo

qplaylearn

www.qplaylearn.com 🇬🇧 (🇮🇹 tra poco!)

MISSION: far conoscere la bellezza della scienza quantistica e sensibilizzare tutti, indipendentemente dall'età o dal background, sull'impatto delle tecnologie quantistiche.

algorithmiq

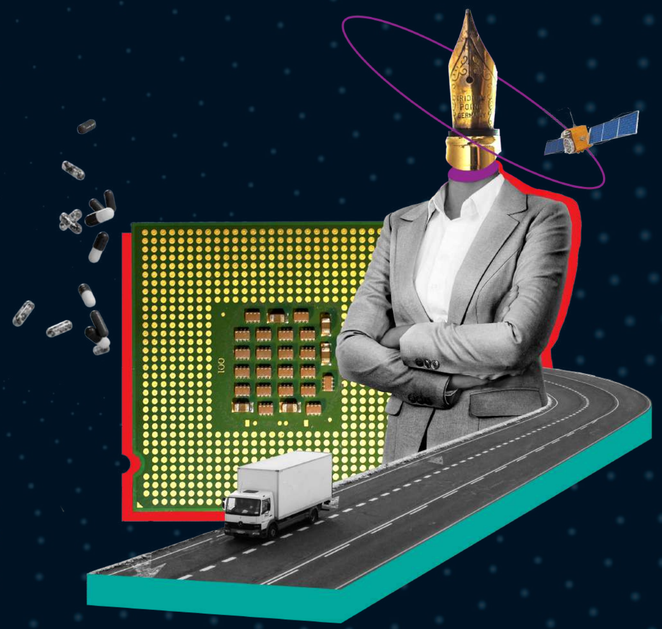
Institute Q

UNIVERSITY OF HELSINKI

Aalto University

EDUCATION

Insegnanti, studenti, e persone curiose



BUSINESS & SOCIETY

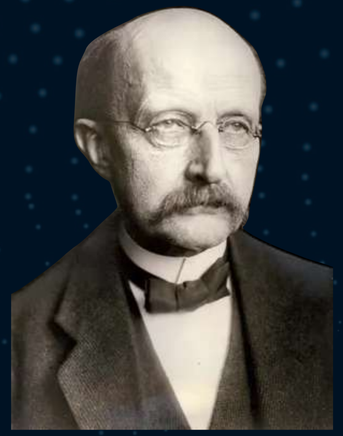
Aziende, policy maker, giornalisti e media

ART & CULTURE

Artisti, curatori, e manager culturali

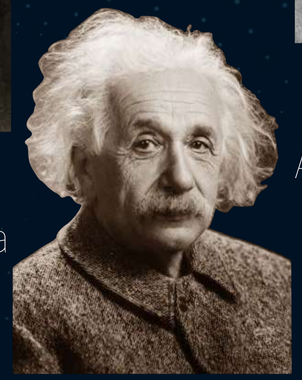
qplaylearn

Meccanica quantistica: from zero to hero



Planck

Energia quantizzata



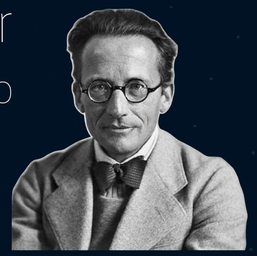
Einstein

Effetto fotoelettrico

Bohr

Atomo quantizzato

Meccanica quantistica



Schördinger

Heisenberg

Pauli

Deutsch, Feynman, Benioff, Manin…

Idea di computer quantistico

Informazione Quantistica

Utilizzo della teoria quantistica

Teoria Informazione e Computazione

(Shannon, Turing, …)

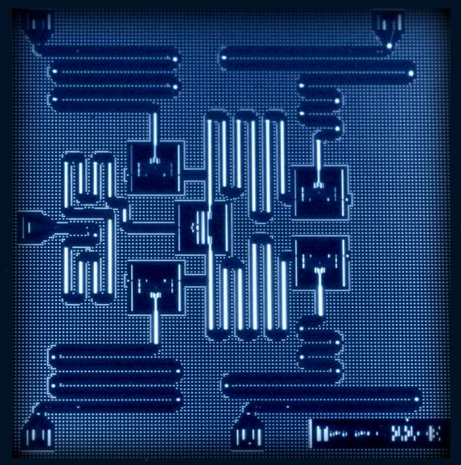
~1900 ~1905 ~1913 … … ~1940 ~1980-90

Meccanica quantistica: from zero to hero

Shor

Fattorizzazione numeri primi
Algoritmi quantistici
Comunicazione quantistica

Ulteriore sviluppo
teorico e sperimentale



IBM

Primo computer quantistico a
5 qubit accessibile via cloud

(prototipi di)

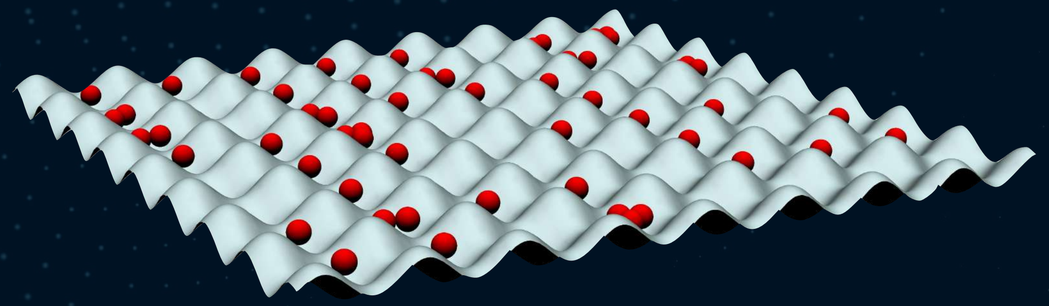
Tecnologie
quantistiche

~1990 ... ~1990-2010 2016 oggi

Tecnologie quantistiche

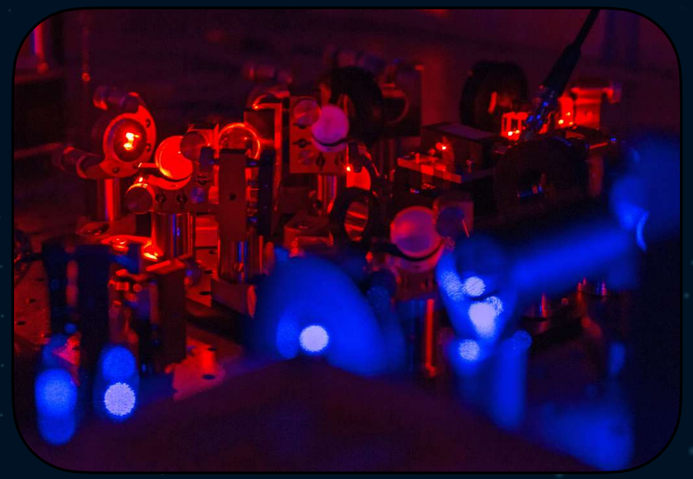
"un nuovo tipo di dispositivi e tecniche capaci di sfuttare proprietà quantistiche per risolvere problemi pratici"

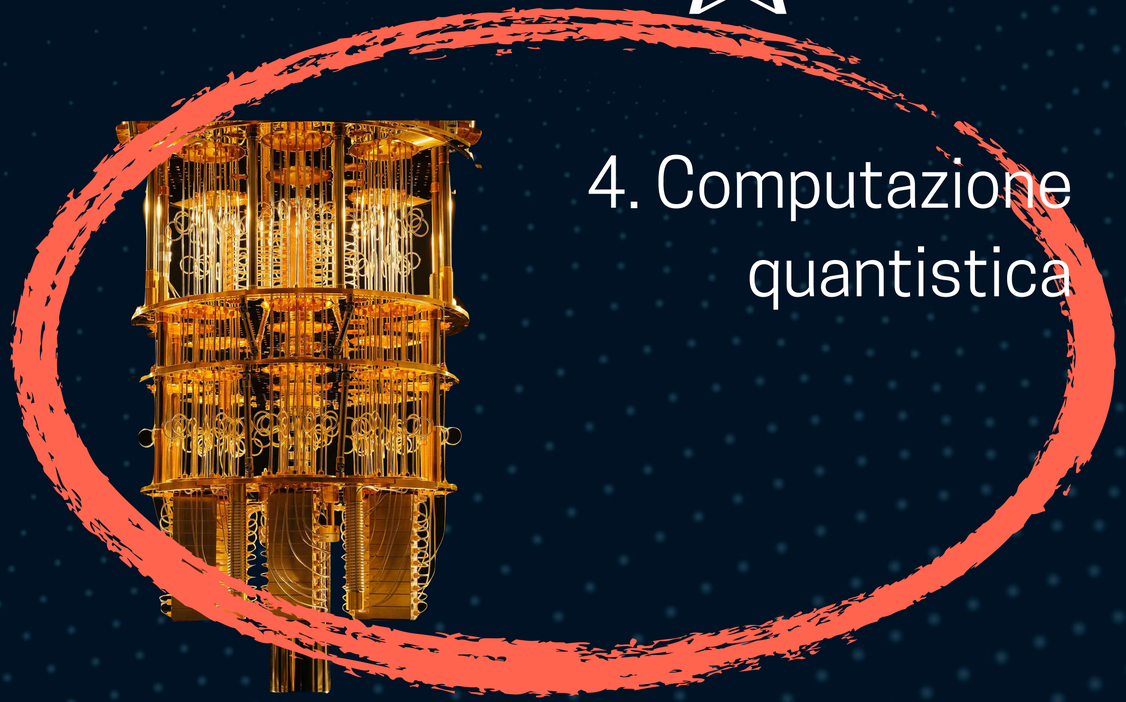
1. Simulatori quantistici



2. Comunicazione quantistica

3. Metrologia/sensoristica quantistica





4. Computazione quantistica

Ma cosa è un computer quantistico?

Ma cosa è un computer ~~quantistico~~?
classico?

Ma cosa è un computer ~~quantistico~~? classico?

Supercomputer Leonardo

Calolatore di Babbage

"Macchina di Turing"

Formulazione astratta di calcolatore

Alan Turing (1936)

“Tutto ciò che può essere calcolato (efficientemente), può essere calcolato (efficientemente) da una Macchina di Turing (probabilistica)”

Tesi di Church-Turing Estesa

“Nature isn’t classical, dammit, and if you want to make a simulation of Nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem because it doesn’t look so easy”

Richard Feynman
(1981)

Possiamo simulare un sistema quantistico su un computer?

No, le risorse necessarie sarebbero troppe!

Feynman, *Simulating Physics with Computers* (1981)
Preskill, *Quantum computing 40 years later* (2023)

“Computing machines resembling the universal quantum computer could, in principle, be built and would have many remarkable properties not reproducible by any Turing machine …”

David Deustch
(1985)

Definizione di una macchina di Turing quantistica, fondamentalmente diversa da una classica, che ha accesso a fenomeni quantistici.

Che cosa può fare?

Deutsch, *Quantum theory, the Church-Turing principle and the universal quantum computer* (1985)

Esempio 1: studiare la natura

Supercomputer attuali più performanti

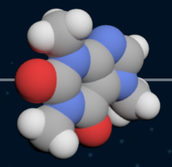
Memoria

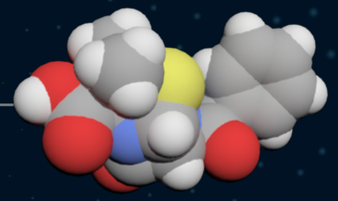
10^4 bits

$\approx 10^{15}$ bits

$\approx 10^{45}$ bits

$\approx 10^{80}$ bits





Molecola

Acqua

Caffeina

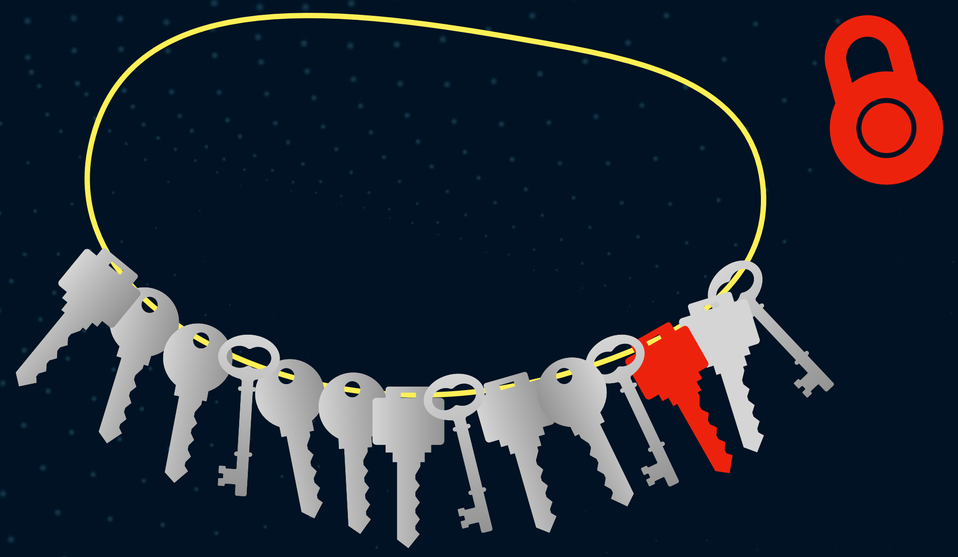
Penicillina

Molecole di queste dimensioni sono già intrattabili anche per i più veloci supercomputer

È un problema quantistico
che necessita una soluzione quantistica

Esempio 2: Algoritmo di Grover

Cercare un oggetto tra N elementi disordinati



Classicamente in media devi provare tutte le chiavi per trovare quella giusta

$$\sim N \text{ operazioni}$$ **Facile**

Quantisticamente, puoi trovare la chiave giusta con sole

$$\sim \sqrt{N} \text{ operazioni!}$$

Più facile!

È un problema classico
che non necessita una soluzione quantistica, ma funziona meglio!

Esempio 3: Algoritmo di Shor

Fattorizzazione di numeri primi

$$N = 2519590847565789349402718324004839857142928212620403202777713783604366202070759555626401852588078440691829064124951508218929855914917618450280848912007284499268739280728777673597141834727026189637501497182469116507761337985909570009733045974880842840179742910064245869181719511874612151517265463228221686998754918242243363725908514186546204357679842338718477444792073993423658482382428119816381501067481045166037730605620161967625613384414360383390441495263443219011465754445417842402092461651572335077870774981712577246796292638635637328991215483143816789988504044536402352738195137863656439121201039712282212072035 7$$

$$N = a \cdot b \cdot c \cdot \cdots$$ con $a, b, c, \cdots$ primi

Classico **Difficile** $\sim \exp(d^{1/3})$

(d è il numero di cifre di N)

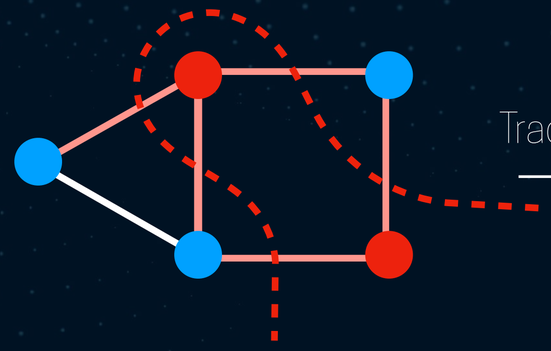
Quantistico **Facile** $\sim d^3$

È un problema classico molto strutturato,
che i computer quantistici possono risolvere in maniera molto più efficiente!

Esempio 4: varie ed eventuali

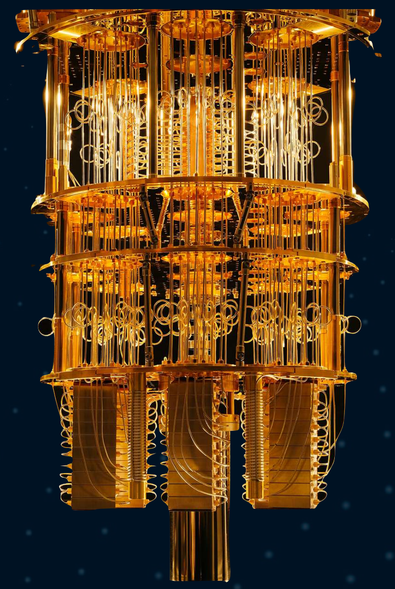
Problemi di ottimizzazione

Machine learning / Portfolio optimisation (finance) / Scheduling tasks / Structured problems



Problema MAXCUT

Traduci su un computer quantistico →

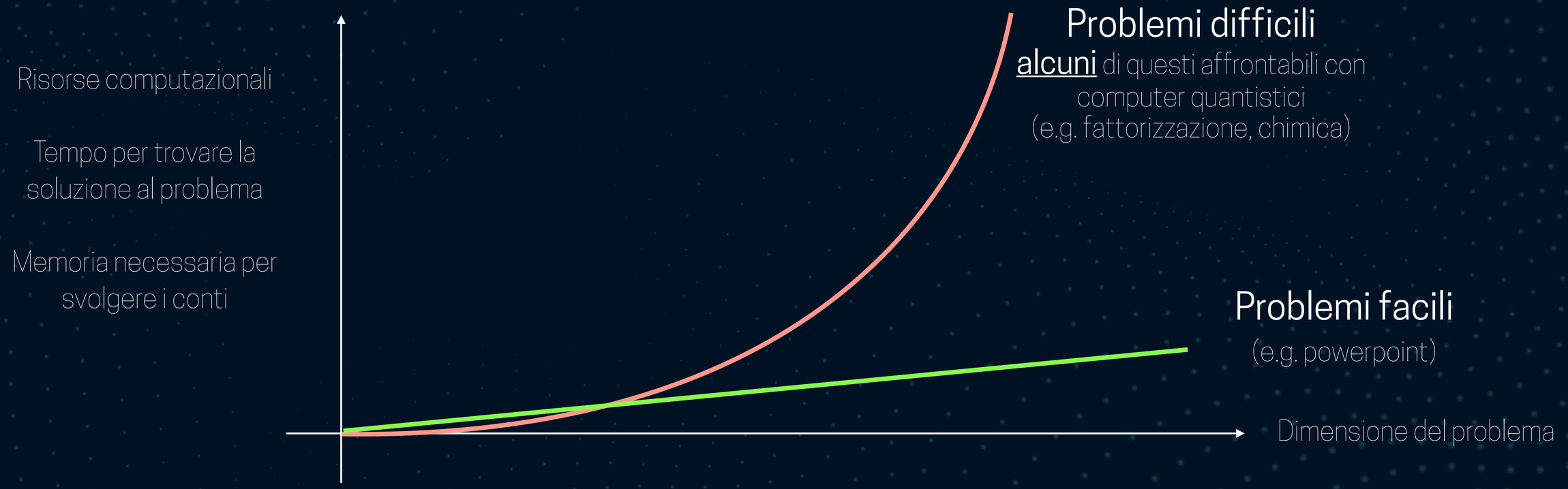


Trova la partizione migiore (e.g. via Quantum Approximate Optimisation Algorithm, QAOA)

I computer quantistici potrebbero offrire un vantaggio computazionale su diversi tipologie di problemi, ma ancora non si sa se e come.

Perché i QC sono/saranno/potrebbero essere utili

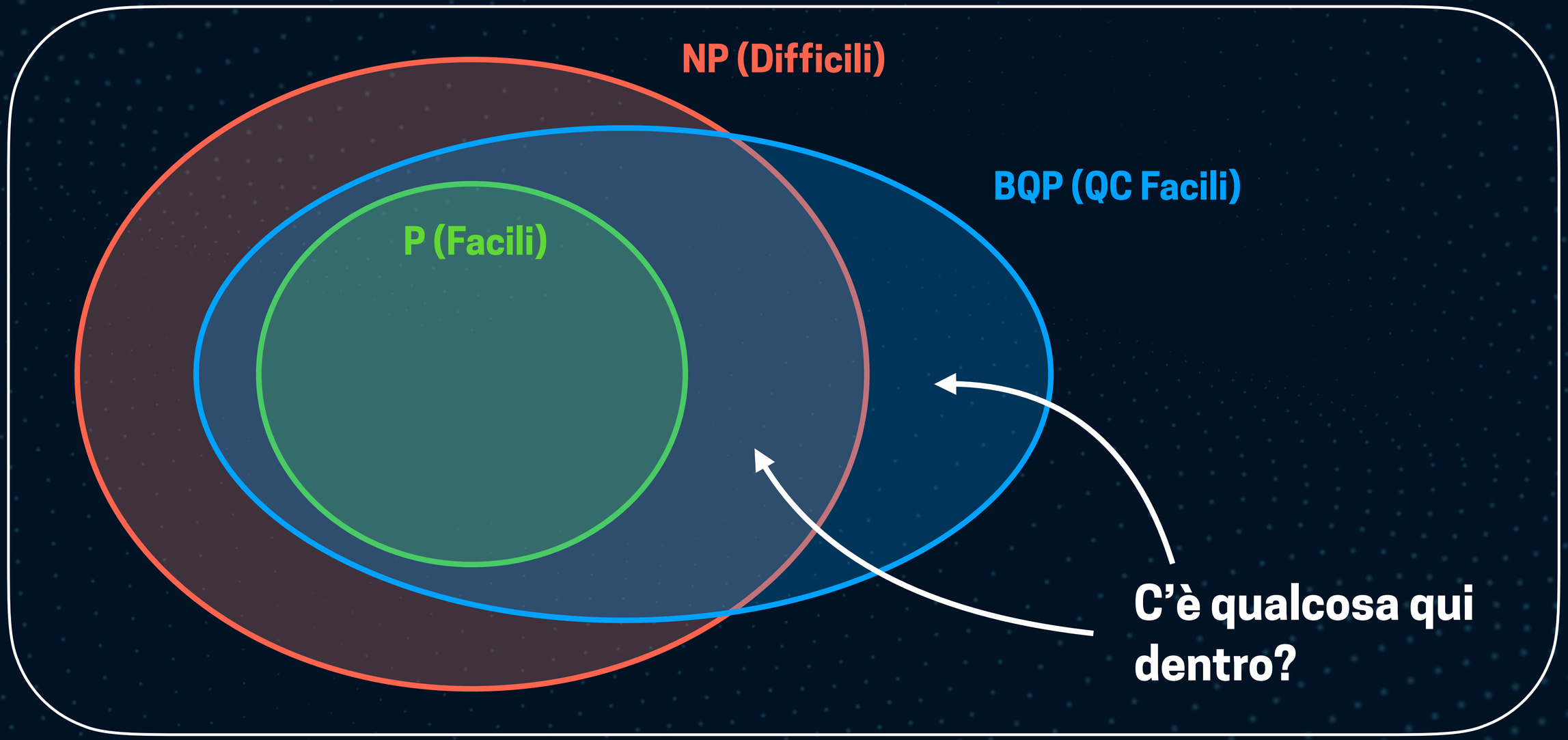
Scaling esponenziale delle risosrse computazionali



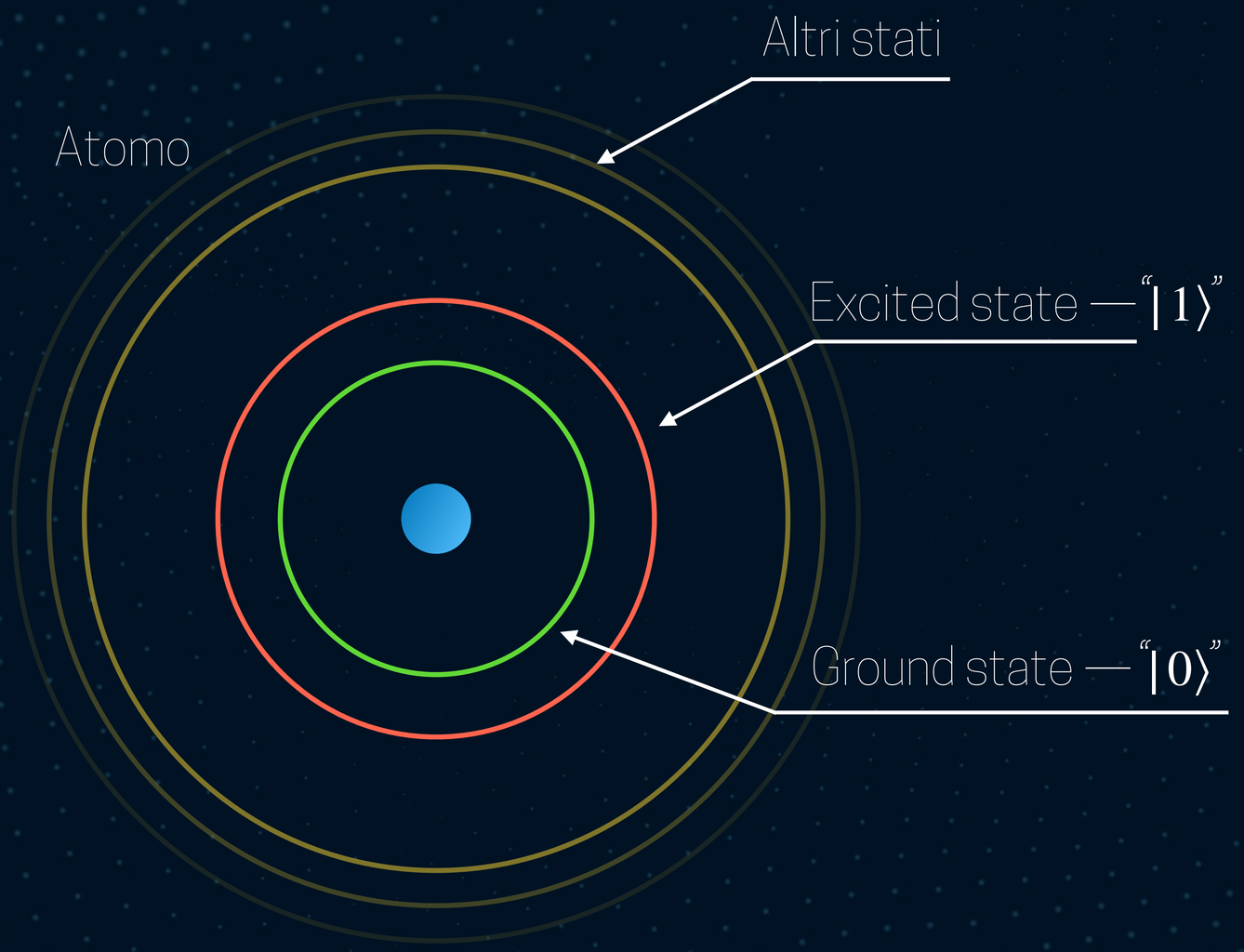
Ci sono problemi che i computer classici non possono risolvere; per tutto il resto c'è la computazione quantistica

[cit. adattata daMastercard]

Complessità computazionale, due spiccioli



Ma quindi, cosa si fa un computer quantistico?



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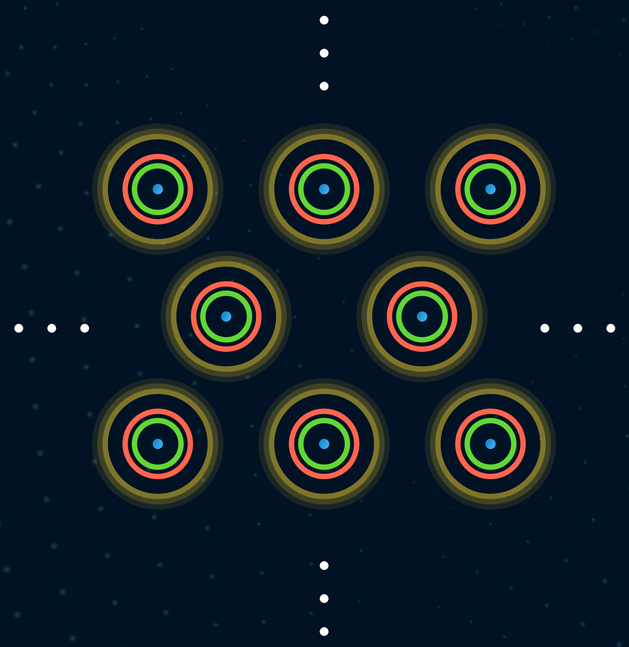
Quantum Bit
"Qubit"

Ma quindi, cosa si fa un computer quantistico?

Quantum computer =

Più qubit insieme

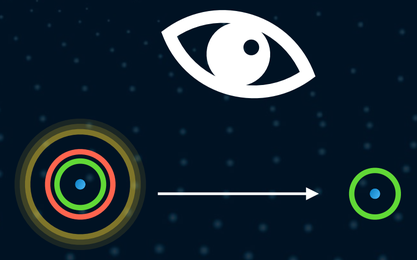


+

Capacità di controllare e operare i qubit

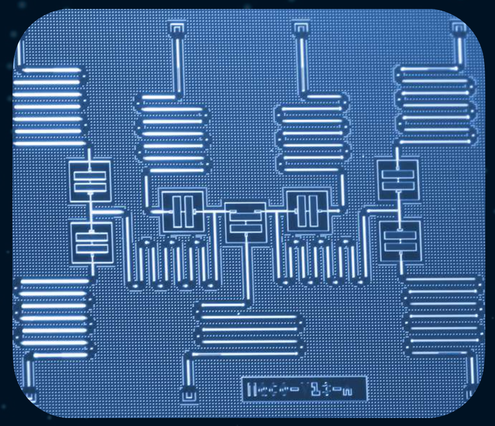
+

Estrarre informazione dal sistema (misurare)



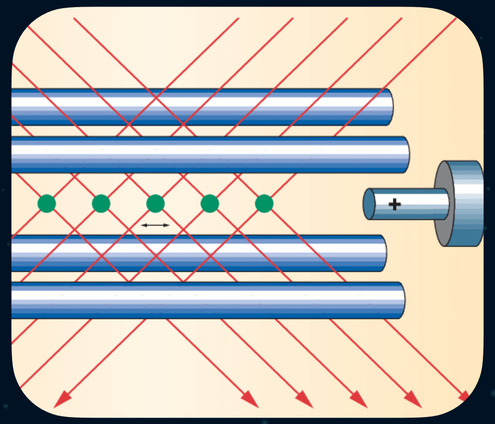
Come costruire un comuter quantistico

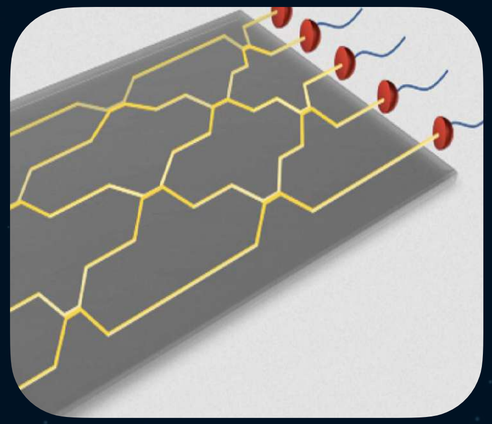
Più tecnologie sono state proposte e utilizzate



Superconducting circuits
(IBM, Google, IQM)

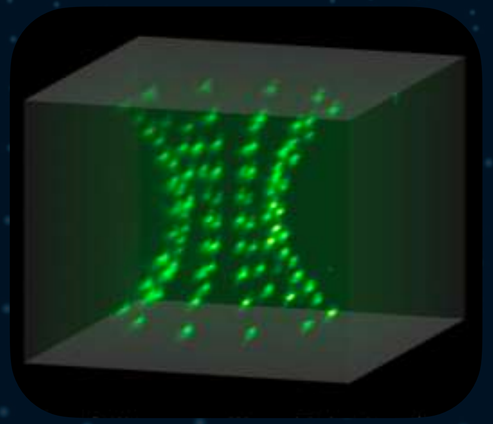
Ion Traps
(IonQ, Quantinuum)





Photonics
(Xanadu, PsiQuantum)

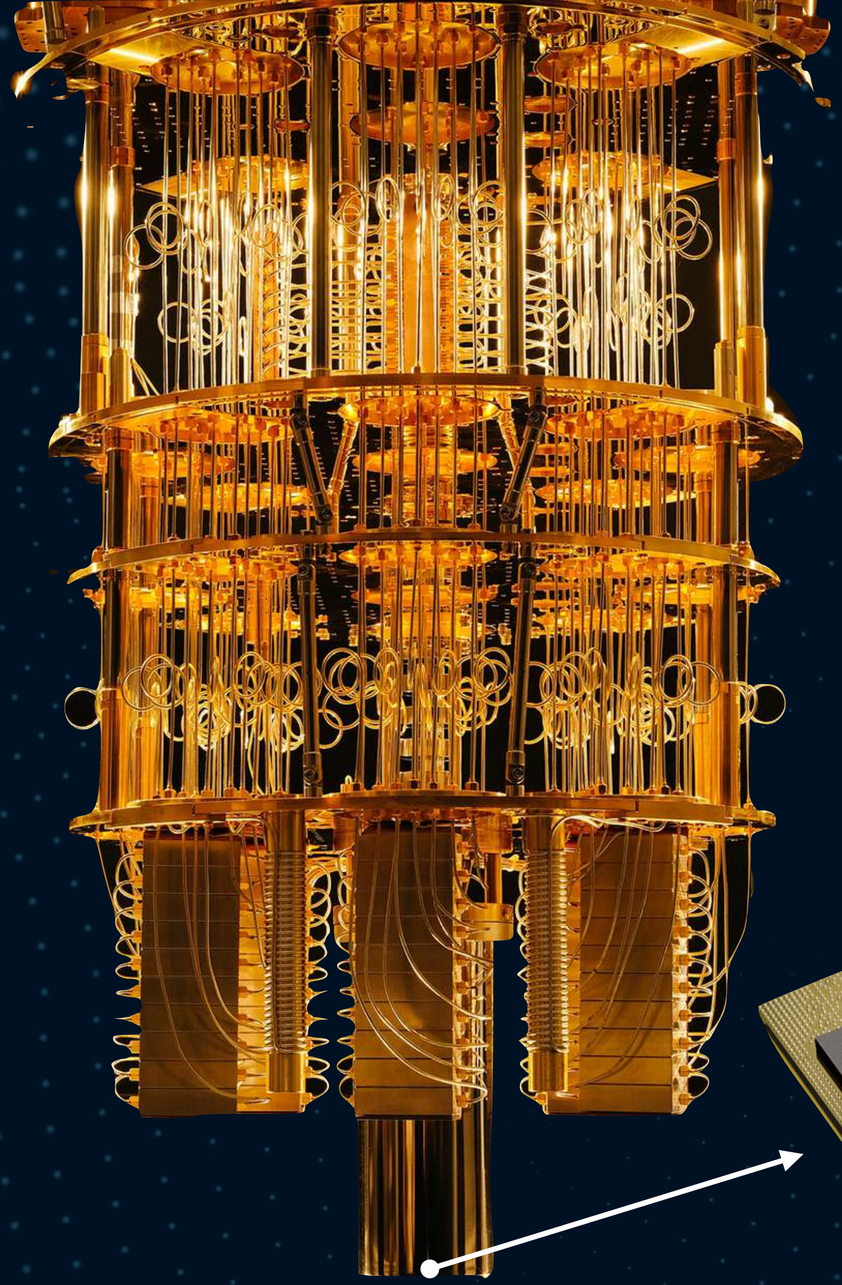
Neutral atoms
(Pasqal)



. . .

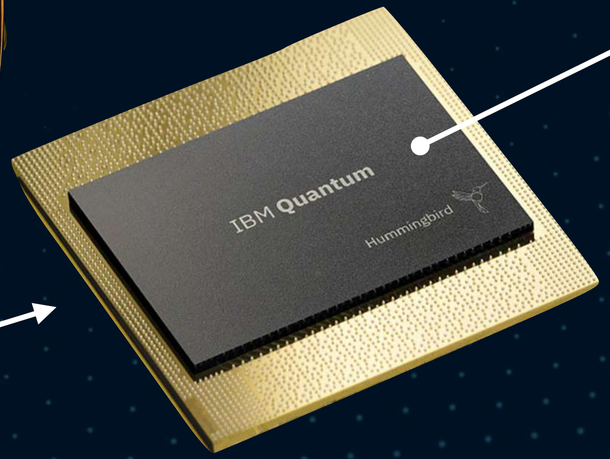
Un Quantum Computer

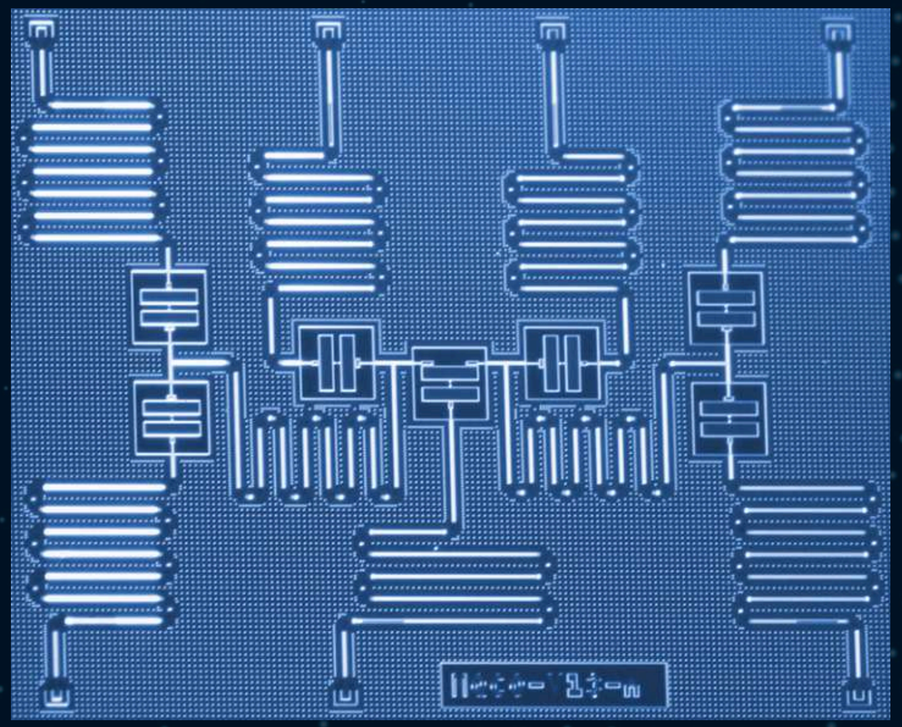
(o meglio, un frigorifero)

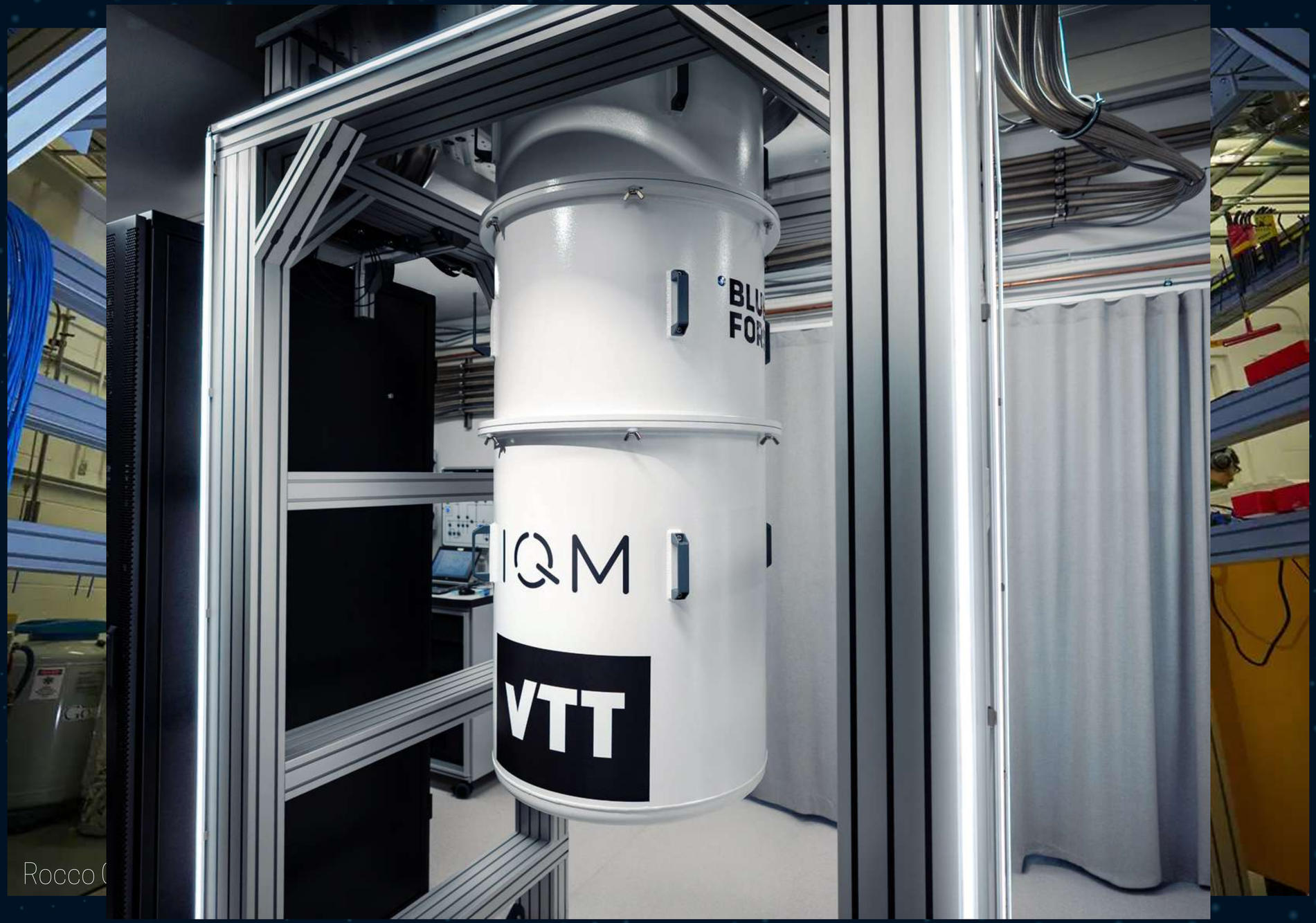


Temperatura di

$-270°C$



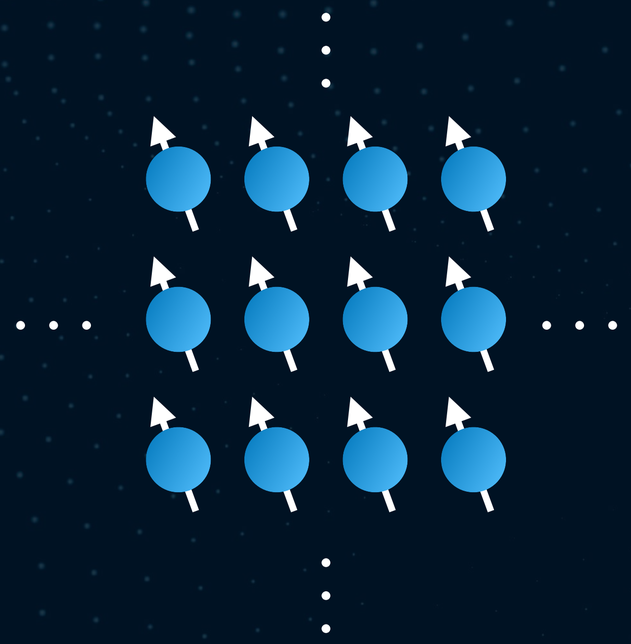


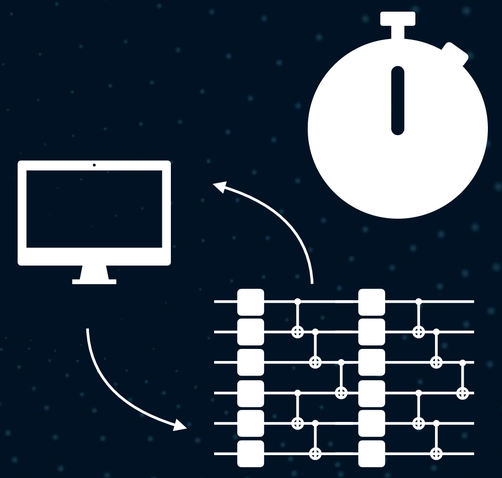


Rocco C

Cosa vorremmo

Ingredienti necessari per avere un computer quantistico *davvero* funzionante





Tanti tanti qubits

Qubit e operazioni di qualità

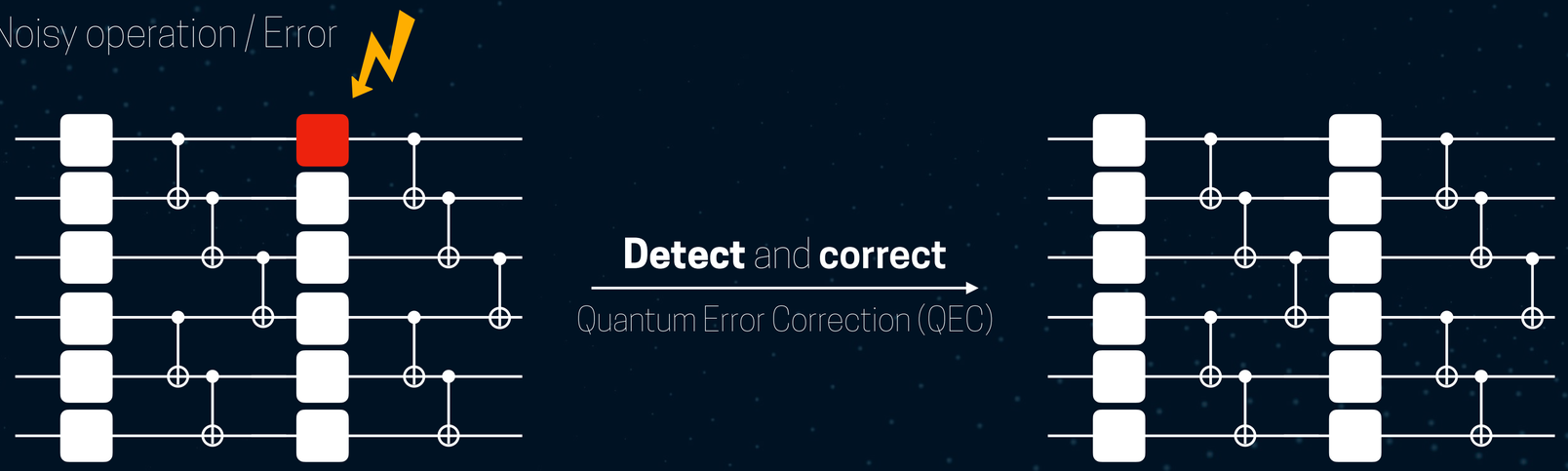
Tempi di esecuzione rapidi

Cosa avremo (si spera)

Computer quantistici che soddisfano i criteri di prima sono chiamati

Fault Tolerant Quantum Computers

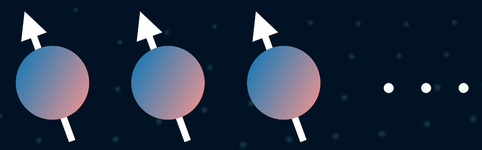
Noisy operation / Error



Un qubit logico

=

Tanti qubit fisici di buona qualità



Usare Algoritmo di Shor su un caso realistico

~ 20 milioni di qubit fisici

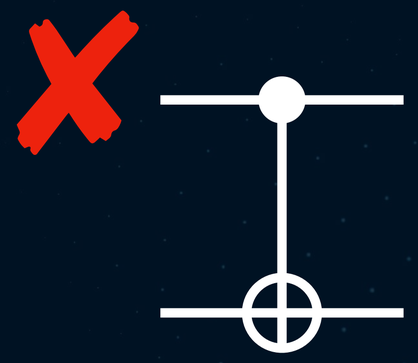
[~ 2000 qubit logico x 1000]

Cosa abbiamo

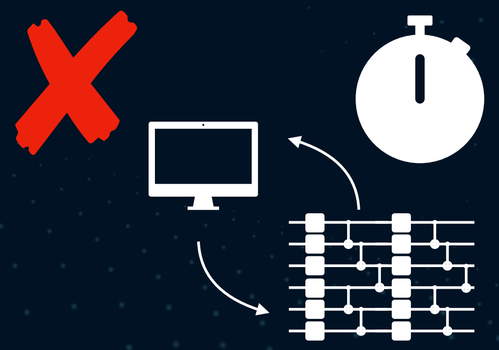
Invece di Fault Tolerant Quantum Computers (FTQC), ora abbiamo i

Noisy Intermediate Scale Quantum (NISQ) computers

qubits ~ 50-100



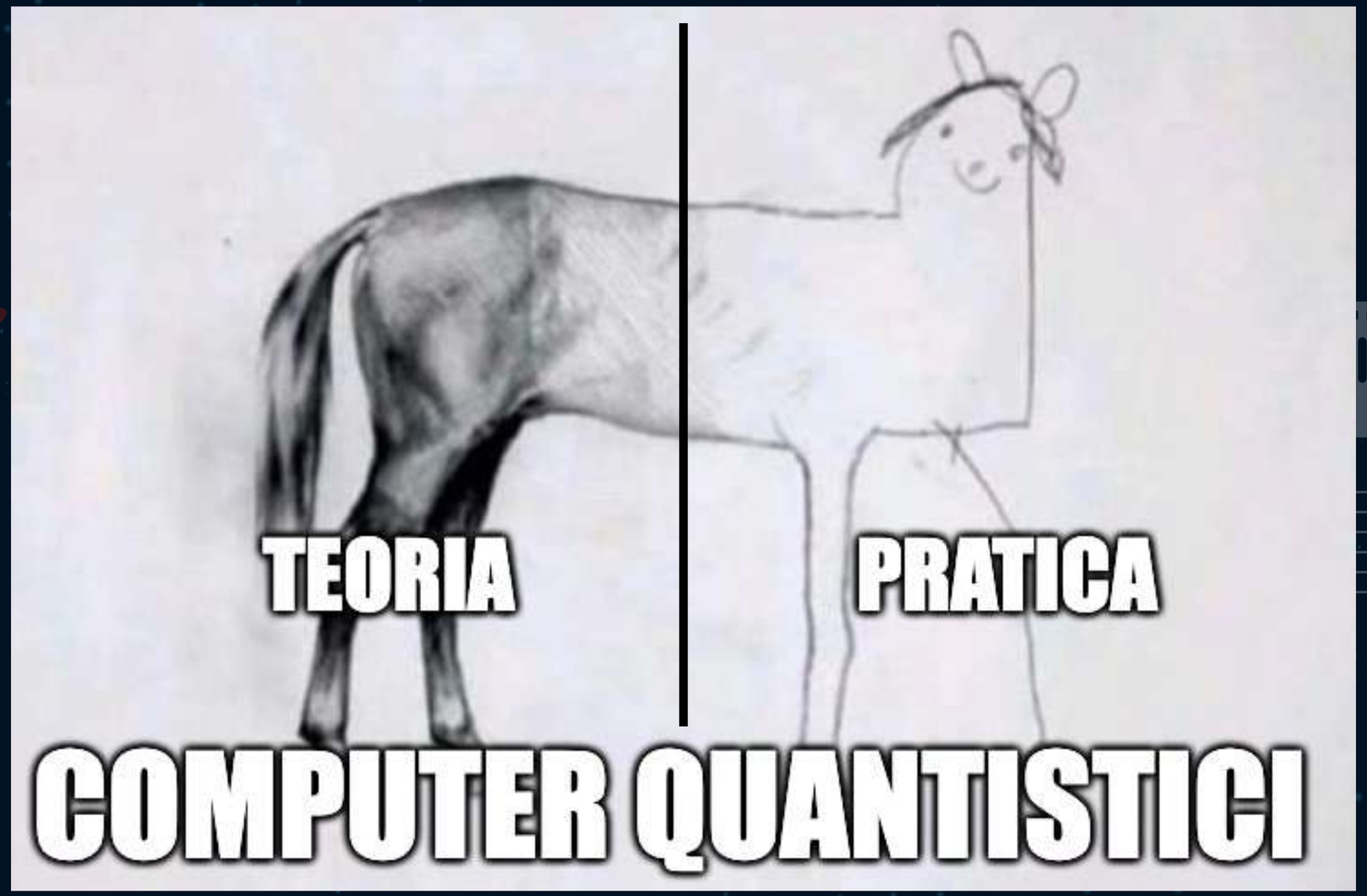
Operazioni imperfette



Lenti e costosi

...ma i prototipi migliorano in fretta!

Cosa abbiamo



Development Roadmap

IBM **Quantum**

	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
	Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing
Data Scientist						Platform						
						Code assistant	Functions	Mapping Collection	Specific Libraries			General purpose QC libraries
Researchers					Middleware							
					Quantum Serverless	Transpiler Service	Resource Management	Circuit Knitting x P	Intelligent Orchestration			Circuit libraries
Quantum Physicist			Qiskit Runtime									
	IBM Quantum Experience		QASM3	Dynamic circuits	Execution Modes	Heron (5K) Error Mitigation 5k gates 133 qubits Classical modular 133x3 = 399 qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (10K) Error Mitigation 10k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (15K) Error Mitigation 15k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Starling (100M) Error correction 100M gates 200 qubits Error corrected modularity	Blue Jay (1B) Error correction 1B gates 2000 qubits Error corrected modularity
	Early Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon Benchmarking 27 qubits		Eagle Benchmarking 127 qubits								

Innovation Roadmap

Software Innovation	IBM Quantum Experience	Qiskit Circuit and operator API with compilation to multiple targets	Application modules Modules for domain specific application and algorithm workflows	Qiskit Runtime Performance and abstract through Primitives	Serverless Demonstrate concepts of quantum centric-supercomputing	AI enhanced quantum Prototype demonstrations of AI enhanced circuit transpilation	Resource management System partitioning to enable parallel execution	Scalable circuit knitting Circuit partitioning with classical reconstruction at HPC scale	Error correction decoder Demonstration of a quantum system with real-time error correction decoder			
Hardware Innovation	Early Canary 5 qubits Penguin 20 qubits Albatross 16 qubits Prototype 53 qubits	Falcon Demonstrate scaling with I/O routing with Bump bonds	Hummingbird Demonstrate scaling with multiplexing readout	Eagle Demonstrate scaling with MLW and TSV	Osprey Enabling scaling with high density signal delivery	Condor Single system scaling and fridge capacity	Flamingo Demonstrate scaling with modular connectors	Kookaburra Demonstrate scaling with nonlocal c-coupler	Demonstrate path to improved quality with logical memory	Cockatoo Demonstrate path to improved quality with logical communication	Starling Demonstrate path to improved quality with logical gates	
						Heron Architecture based on tunable-couplers	Crossbill m- coupler					

Executed by IBM

On target

IBM Quantum / © 2023 IBM Corporation

Quantum ~~Supremacy~~ ~~Advantage~~ ~~Utility~~ Usefulness

nature

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, K
Sergio Boixo,
Roberto Collin
Gidney, Mariss

2019
Task artificiale su 50 qubit
Simulabile classicamente in un paio di minuti (invece di 10000 anni)

nature

IBM

Article | Open access | Published: 14 June 2023

Evidence for the utility of quantum computing before fault tolerance

Youngseok Kim, Andrew Ec
Rosenblatt, Hasan Nayfeh, Ya

2023, 127 qubits
Task fisicamente interessante
Difficile, ma fattibile su un computer classico in qualche minuto (con nuove tecniche)

Science

D:wave
The Quantum Computing Company™

RESEARCH ARTICLE

Beyond-classical computation in quantum simulation

ANDREW D. KING, ALBERTO NOCERA, M
, [...], AND MOHAMMAD H. AMIN +5

SCIENCE · 12 Mar 2025 · First Releas

2024/2025
Stessa cosa di sopra

QUANTINUUM

[Submitted on 26 Mar 2025]

Digital quantum magnetism at the frontier of classical simulations

Reza Haghshenas, Eli Chertkov, Michael Mills, Wilhelm Kadow, Sheng-Hsuan Lin, Yi-Hsiang Chen, Chris Cade, Ido Niesen, Tomislav Begušić, Manuel S. Rudolph, Cristina Cirstoiu, Kevin Hemery, Conor Mc Keever, Michael Lubasch, Etienne Granet, Charles H. Baldwin, John P. Bartolotta, Matthew Bohn, Julia

3 giorni fa
Stiamo a vedere…

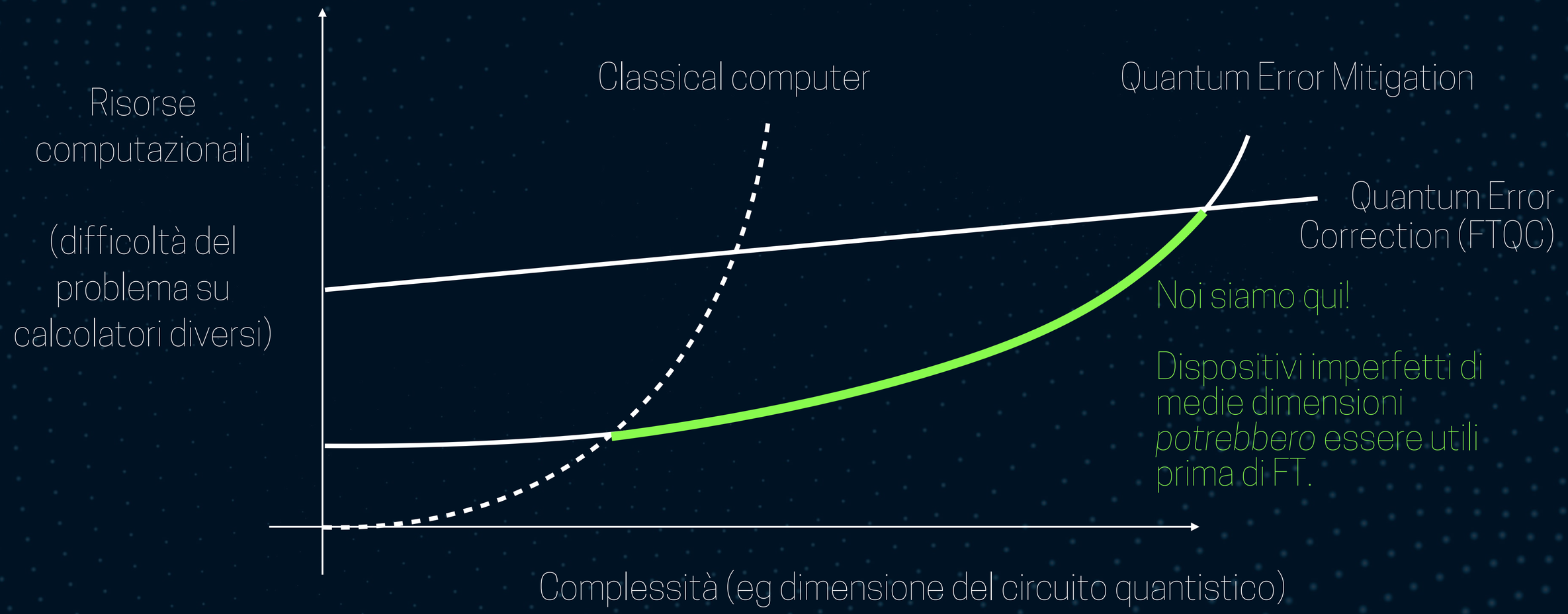
Status of NISQ applications

What we have now. NISQ is valuable for scientific exploration. But there is no proposed application of NISQ computing with *commercial* value for which quantum advantage has been demonstrated *when compared to the best classical hardware running the best algorithms for solving the same problems*.

What we can reasonably foresee. Nor are there persuasive theoretical arguments indicating that commercially viable applications will be found that do *not* use quantum error-correcting codes and fault-tolerant quantum computing.

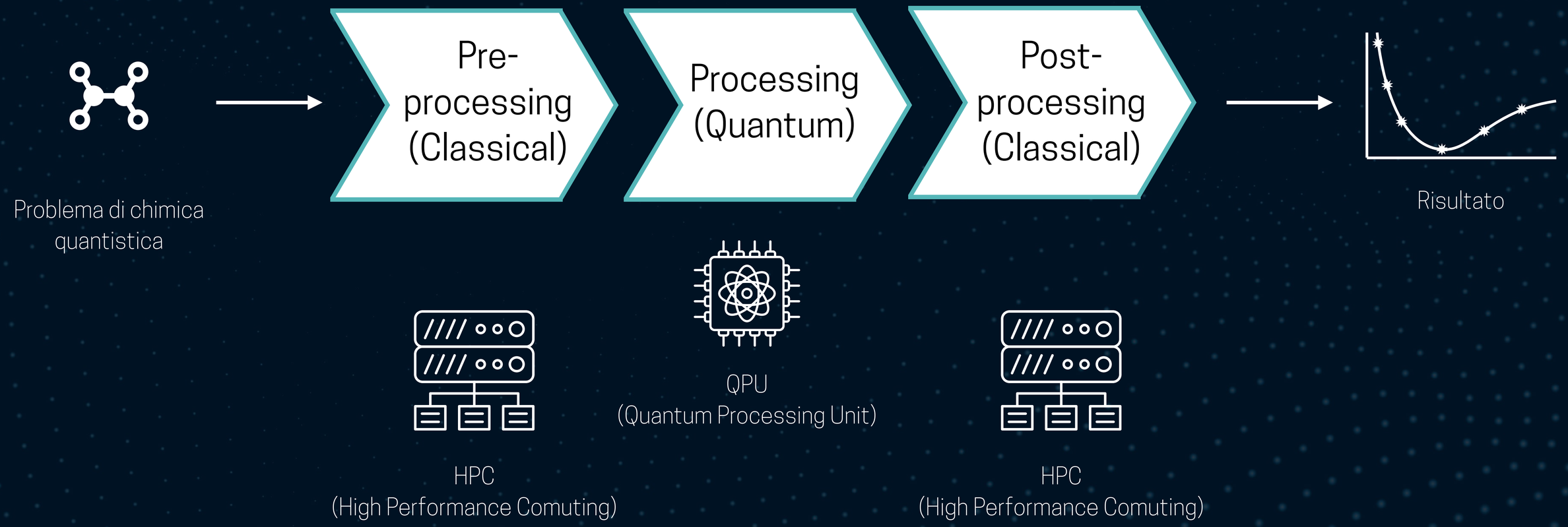
Preskill, Q2B conference (2023)

Make it (mitigation), until you make it (correction)



Sinergia fra classico e quantistico

Combinare il meglio di entrambi per una computazione migliore



Sinergia fra classico e quantistico

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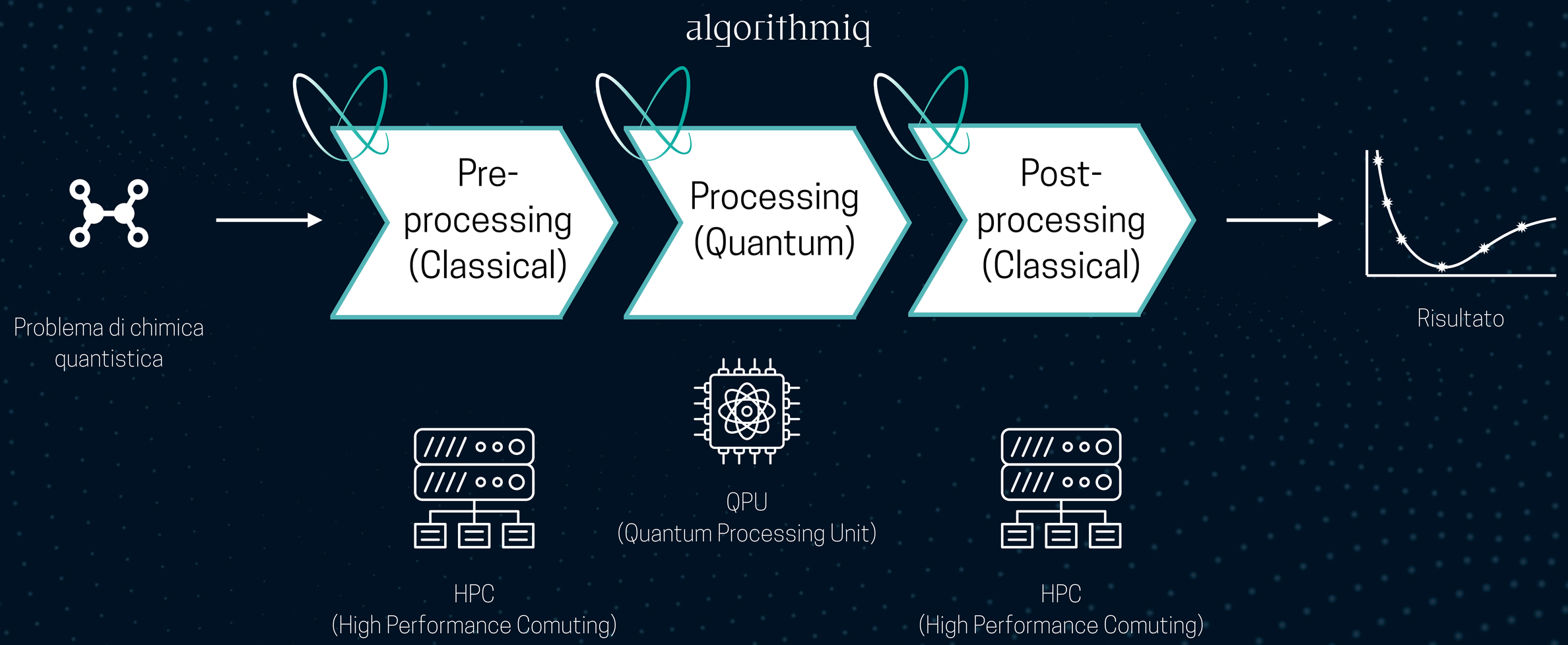


Riassunto della Parte I (a)

I computer quantistici sono calcolatori che sfruttano i principi della meccanica quantistica. Potrebbero offire vantaggi computazionali su più problemi, dall'ottimizzazione alle scienze naturali.

I computer quantistici attuali sono limitati in termini di dimensione e accuratezza, ma la tecnologia per costruirli migliora in fretta. È un campo molto attivo a livello sperimentale, teorico e software.

Mentre si procede verso computer quantistici con correzione degli errori, i dispositivi odierni denominati NISQ sono usati in tandem con computer classici performanti.

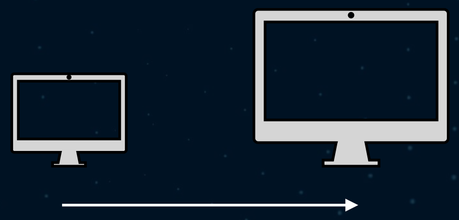
Sebbene imperfetti, i dispositivi attuali sono un utile strumento di ricerca scientifica, e una convicente prova di utilià quantistica potrebbe essere dietro l'angolo.

the end, of Part I

Parte I (b)

Computazione quantistica: nel dettaglio

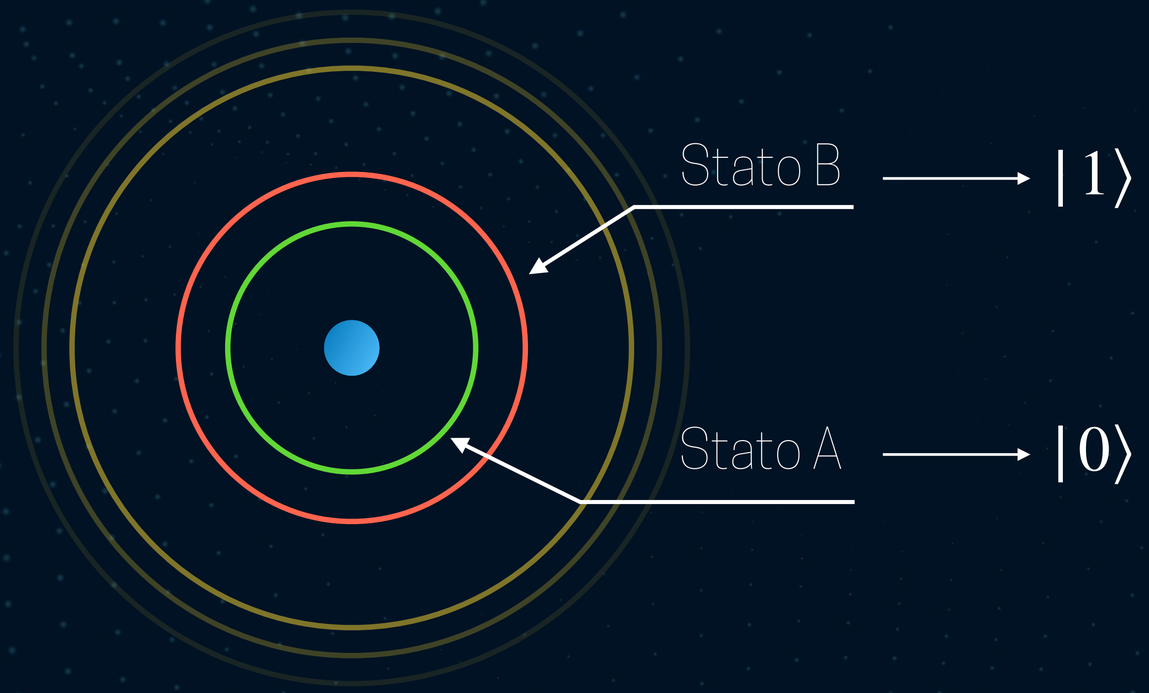
(slides, ~40min)



Come si fa?

Le basi della computazione quantistica

o come vi tocca studiare per bene l'algebra lineare



Qubit:
unità elementare di informazione quantistica. Utilizzato per codificare e processare informazioni sui computer quantistici.

Equivalente quantistico del bit classico.

Matematicamente, lo stato di un qubit è descritto dalla *combinazione lineare* di due stati:

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

Sovrapposizione!

Bit vs. Qubit

Bit

0 1

Qubit

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

Sovrapposizione!

La notazione di Dirac

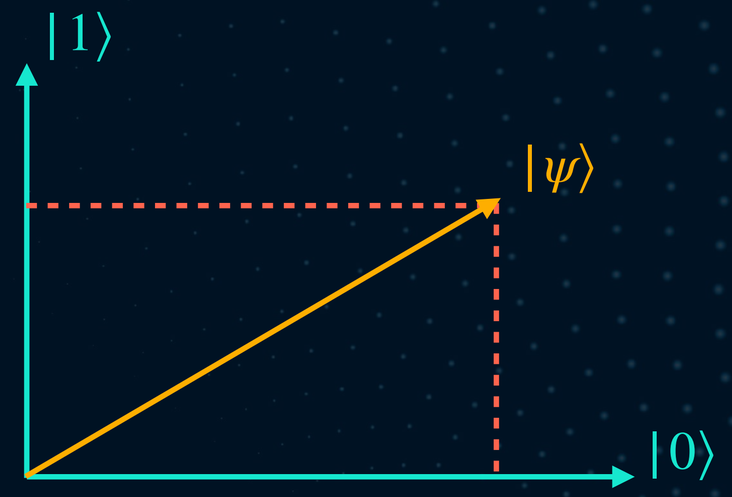
Ovvero un modo alternativo di rappresentare dei vettori

Stato del qubit = vettore in uno spazio di Hilbert

Coefficienti complessi, $\alpha, \beta \in \mathbb{C}$

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

Vettori di base
(fisicamente, autostati del sistema quantistico)



$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$|\psi\rangle = [\alpha, \beta]$$

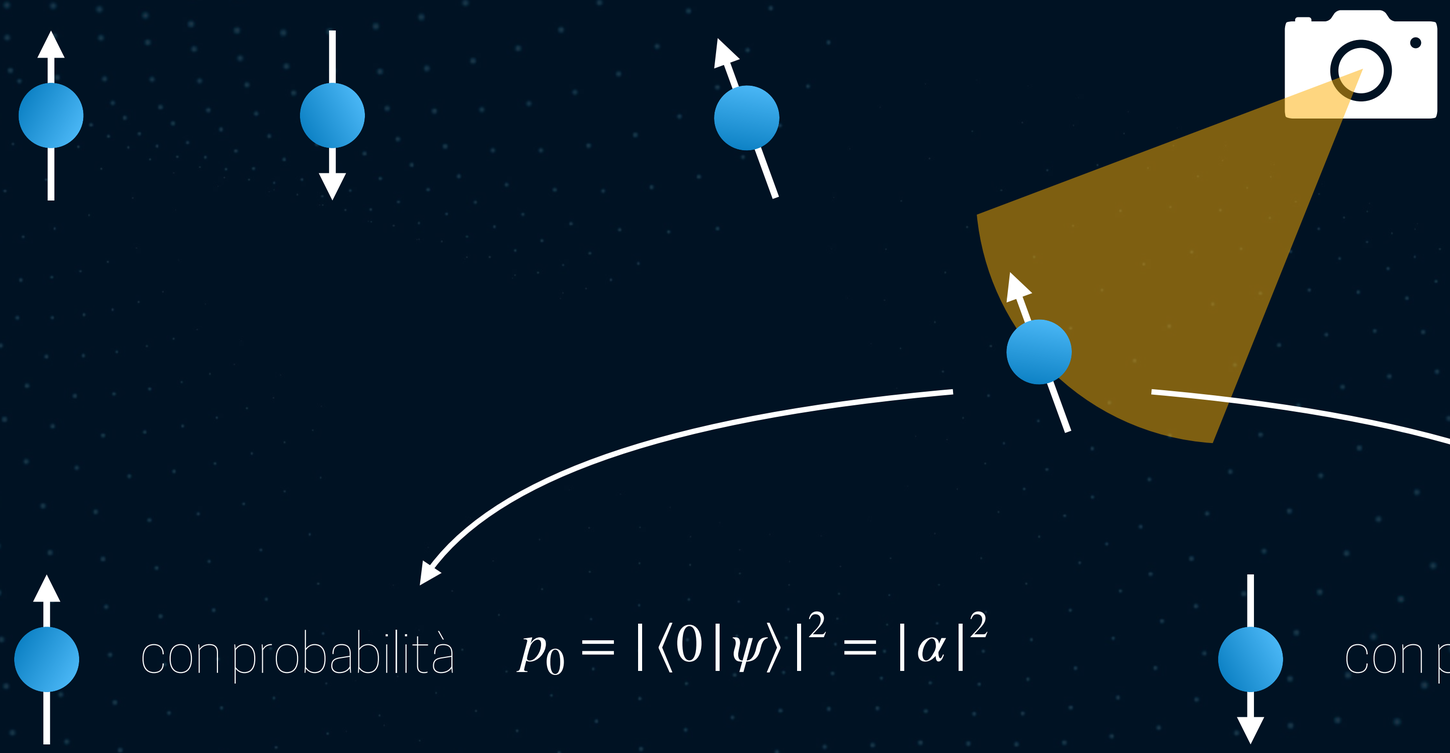
Stato normalizzato: $\langle\psi|\psi\rangle = |\alpha|^2 + |\beta|^2 = 1$

Perché lo stato è normalizzato?

o come introduciamo la natura probabilistica della meccanica quantistica

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

Misura / Osservazione



$$1 = p_0 + p_1 = |\alpha|^2 + |\beta|^2$$

con probabilità $p_0 = |\langle 0|\psi\rangle|^2 = |\alpha|^2$

con probabilità $p_1 = |\langle 1|\psi\rangle|^2 = |\beta|^2$

Collasso della funzione d'onda / Regola di Born

Operazioni sui qubit

o dove scopriamo a cosa servono le matrici unitarie

matrice

Vettori $\vec{v} \rightarrow \vec{v}' = M\vec{v}$

matrice *unitaria*

Stato quantistico $|\psi\rangle \rightarrow |\psi'\rangle = U|\psi\rangle$

$$U = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \qquad U^\dagger = (U^*)^T = \begin{bmatrix} a^* & c^* \\ b^* & d^* \end{bmatrix} \qquad UU^\dagger = U^\dagger U = \mathbb{1}$$

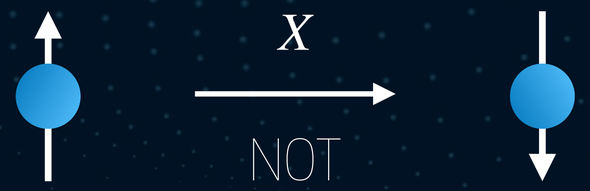
$$\langle\psi'|\psi'\rangle = \langle\psi|U^\dagger U|\psi\rangle = \langle\psi|\psi\rangle = 1$$

Perché matrici unitarie?
Perché preservano la norma (lunghezza) dei vettori!

Esempi di gate quantistici

equivalenti quantistici delle porte logiche classiche

$|0\rangle$ $\xrightarrow[\text{NOT}]{X}$ $|1\rangle$



$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \qquad X|0\rangle = |1\rangle \qquad X|1\rangle = |0\rangle$$

$|0\rangle$ $\xrightarrow[\text{Hadamard}]{H}$ $\frac{|0\rangle + |1\rangle}{\sqrt{2}}$

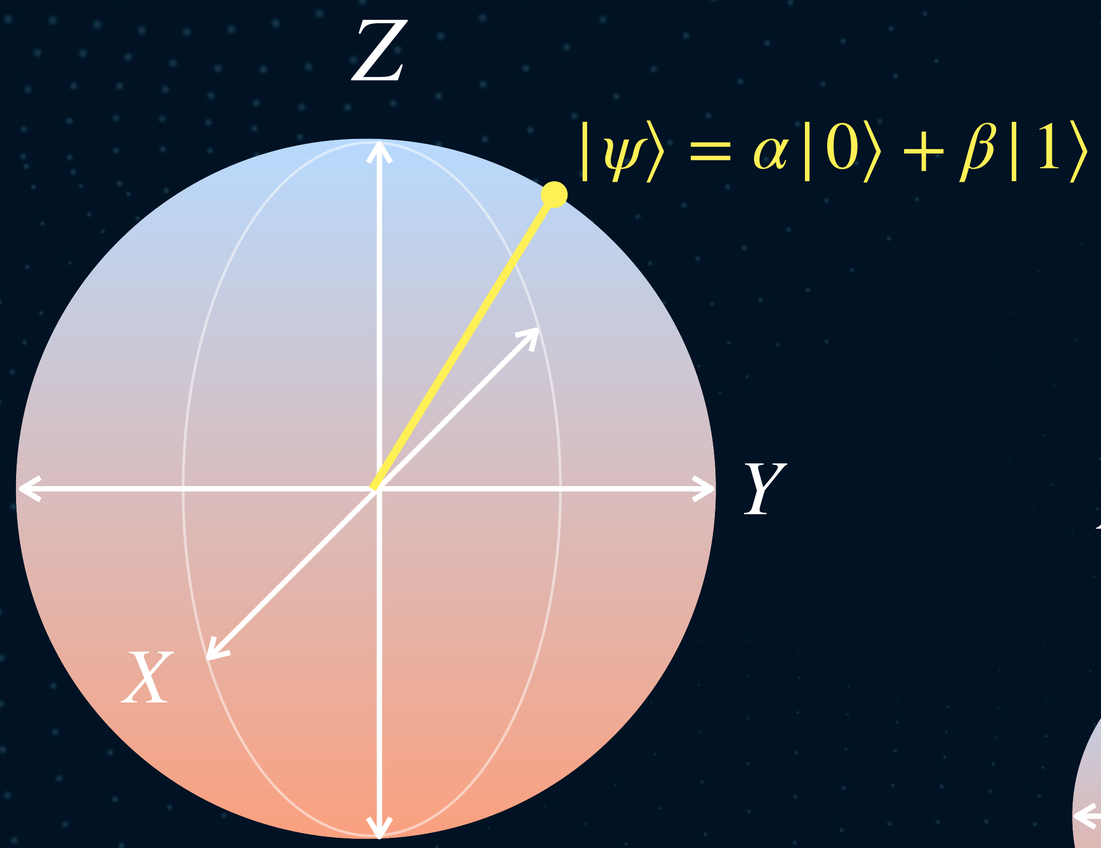
$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad |+\rangle = H|0\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad H|1\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

$|0\rangle$ $\xrightarrow[\text{Unitaria}]{U}$ $|\psi\rangle$

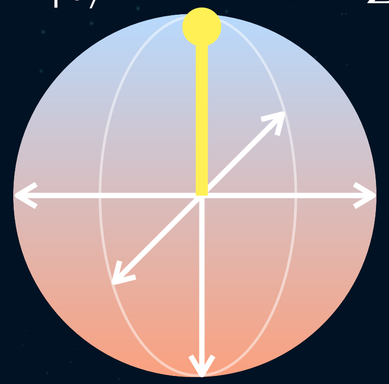
$$U(\theta, \phi, \lambda) = \begin{bmatrix} \cos(\theta/2) & e^{-i\lambda}\sin(\theta/2) \\ e^{i\phi}\cos(\theta/2) & e^{i(\phi+\lambda)}\cos(\theta/2) \end{bmatrix}$$

Sfera di Bloch

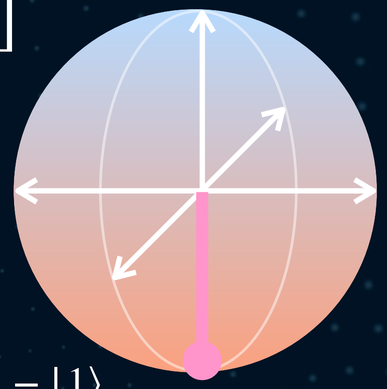
e le matrici di Pauli X, Y, Z



$Z|0\rangle = |0\rangle$



$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$



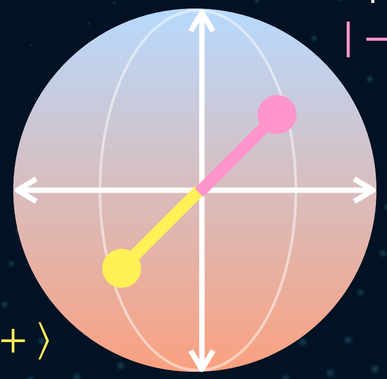
$Z|1\rangle = -|1\rangle$

$|1\rangle$

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$X|-\rangle = -|-\rangle$

$|-\rangle$



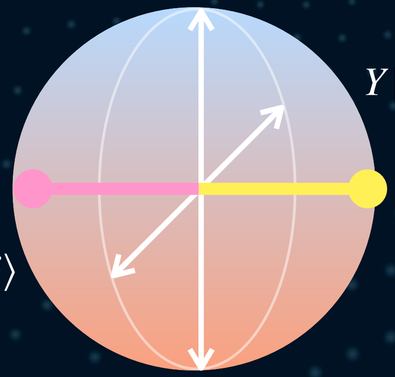
$X|+\rangle = |+\rangle$

$|+\rangle$

$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

$Y|+i\rangle = |+i\rangle$

$|-i\rangle$



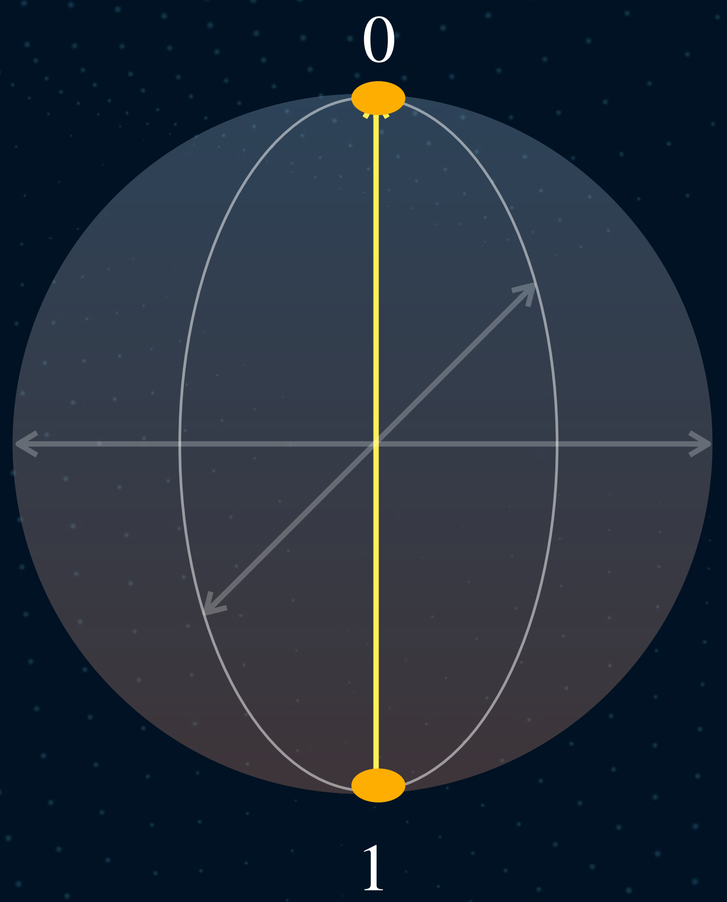
$|+i\rangle$

$Y|-i\rangle = -|-i\rangle$

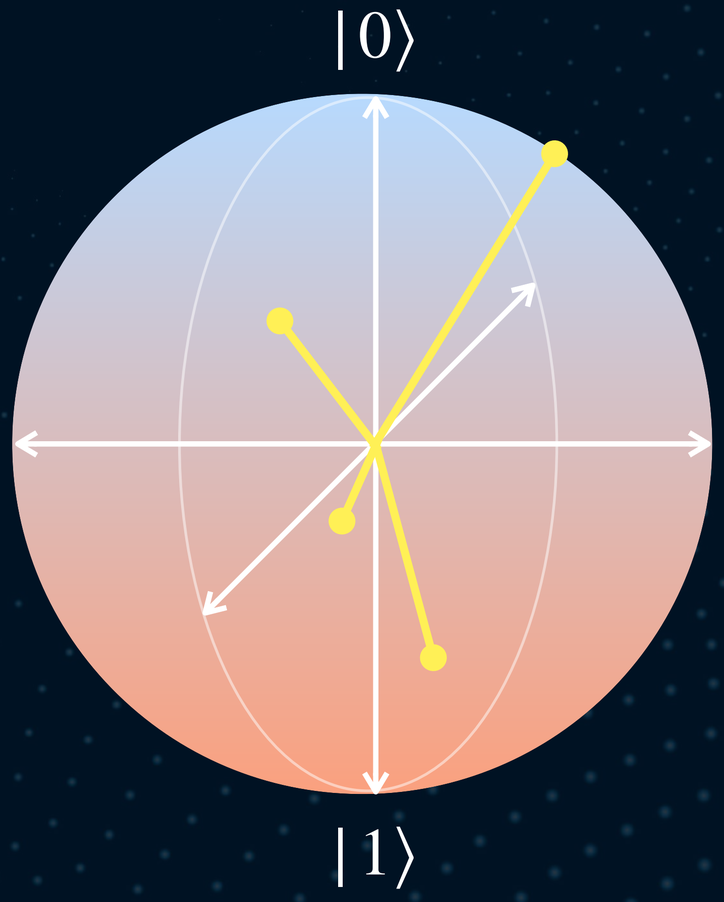
Bit (probabilistici) vs qubit, revisited

se lancio una monetina e non guardo cosa esce…

Bit

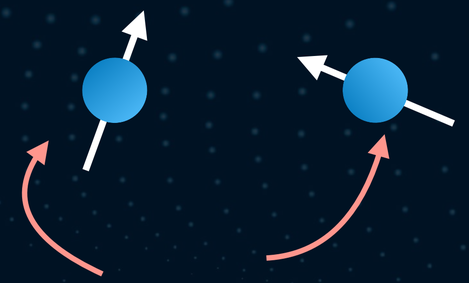


Qubit



Sistemi di più qubit

Stato a due qubit e più qubit



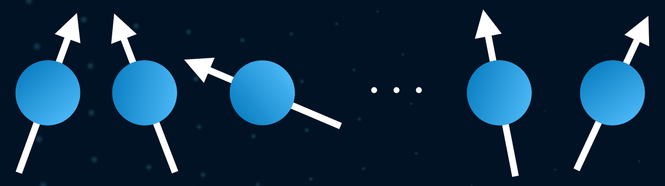
$$|\psi\rangle = \alpha|00\rangle + \beta|01\rangle + \delta|10\rangle + \gamma|11\rangle$$

$$|\alpha|^2 + |\beta| + |\delta|^2 + |\gamma|^2 = 1$$

Dimensione dello spazio di Hilbert di 2 qubit $= 4$

Dimensione dello spazio di Hilbert di ciascun vettore $= 2$

Se abbiamo n qubit:



$$|\psi\rangle = \alpha|00\ldots0\rangle + \beta|00\ldots1\rangle + \cdots + \gamma|11\ldots1\rangle$$

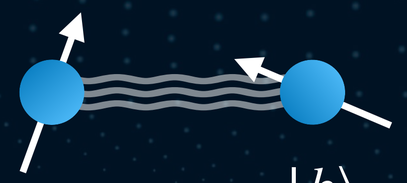
2^n coefficienti complessi! Anche solo salvare su un computer classico richiederebbe una memoria esponenzialmente grande!

Dimensione dello spazio di Hilbert di n qubit? $= 2^n$

$$n = 50 \implies 2 \times 4 \text{ Bytes} \times 2^{50} \approx 10^{16} \text{ Bytes} = 10^7 \text{ GB}$$

Operazioni a due qubit

come fare interagire due qubit



$|b\rangle$

$b \in \{0,1\}$

	Qubit 1		Qubit 2
If	$|0\rangle$	then	$|b\rangle$
If	$|1\rangle$	then	$X|b\rangle$

$\mathrm{CX}|00\rangle = |00\rangle$ $\quad$ $\mathrm{CX}|10\rangle = |11\rangle$

$\mathrm{CX}|01\rangle = |01\rangle$ $\quad$ $\mathrm{CX}|11\rangle = |10\rangle$

$$|00\rangle = |0\rangle \otimes |0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1 \cdot \begin{bmatrix}1\\0\end{bmatrix}\\ 0 \cdot \begin{bmatrix}1\\0\end{bmatrix}\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}$$

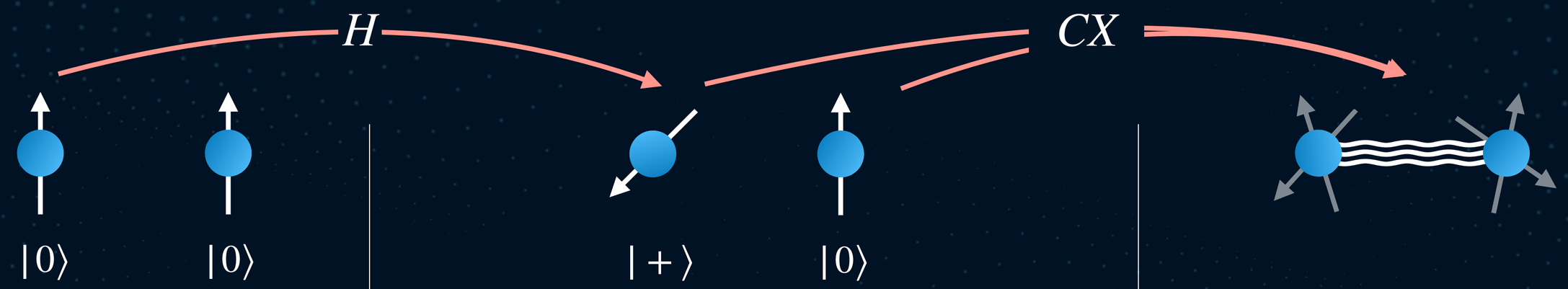
$$\mathrm{CNOT} = \begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$$

$|00\rangle = |0\rangle \otimes |0\rangle = [1 \quad 0 \quad 0 \quad 0]^T$ $\quad$ $|10\rangle = |1\rangle \otimes |0\rangle = [0 \quad 0 \quad 1 \quad 0]^T$

$|01\rangle = |0\rangle \otimes |1\rangle = [0 \quad 1 \quad 0 \quad 0]^T$ $\quad$ $|11\rangle = |1\rangle \otimes |1\rangle = [0 \quad 0 \quad 0 \quad 1]^T$

Finalmente…l'entanglement

Altrimenti noto come"strana azione a distanza" (cit. Einstein)



$$|\psi_0\rangle = |0\rangle \otimes |0\rangle$$

$$|\psi_1\rangle = H|0\rangle \otimes |0\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right) \otimes |0\rangle$$

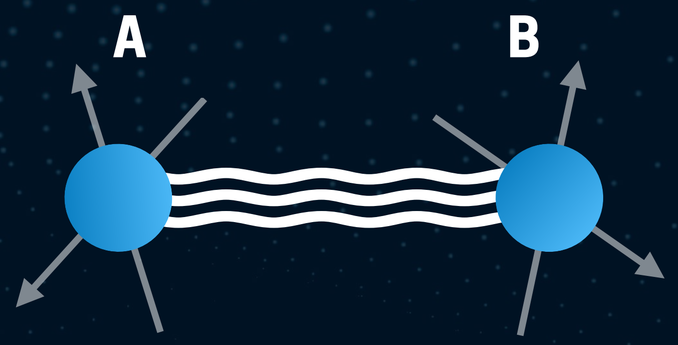
$$= \frac{1}{\sqrt{2}}\left(|00\rangle + |10\rangle\right)$$

$$|\psi_2\rangle = \mathrm{CX}\left[\frac{1}{\sqrt{2}}\left(|00\rangle + |10\rangle\right)\right]$$

$$= \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$

Finalmente…l'entanglement

anche noto come"strana azione a distanza" (cit. Einstein)



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0_A 0_B\rangle + |1_A 1_B\rangle\right)$$

Andiamo a calcolare le probabilità dei possibili risultati di misura su questo stato:

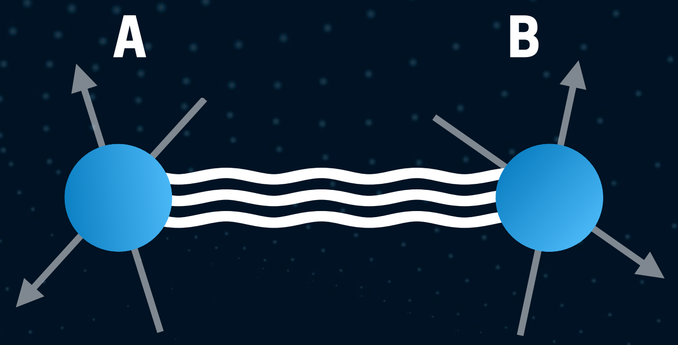
$$p(A=0, B=0) = |\langle 0_A 0_B|\psi\rangle|^2 = \left|\frac{1}{\sqrt{2}}\left(\langle 00|00\rangle + \langle 00|11\rangle\right)\right|^2 = \frac{1}{2}$$

$$p(A=1, B=1) = |\langle 1_A 1_B|\psi\rangle|^2 = \frac{1}{2}$$

$$p(A=0, B=1) = p(A=1, B=0) = 0$$

Finalmente…l'entanglement

anche noto come"strana azione a distanza" (cit. Einstein)



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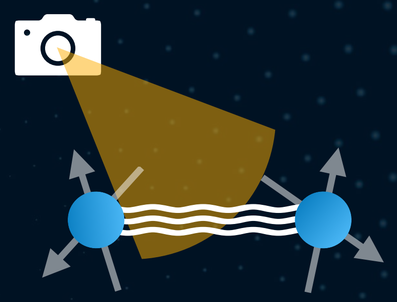

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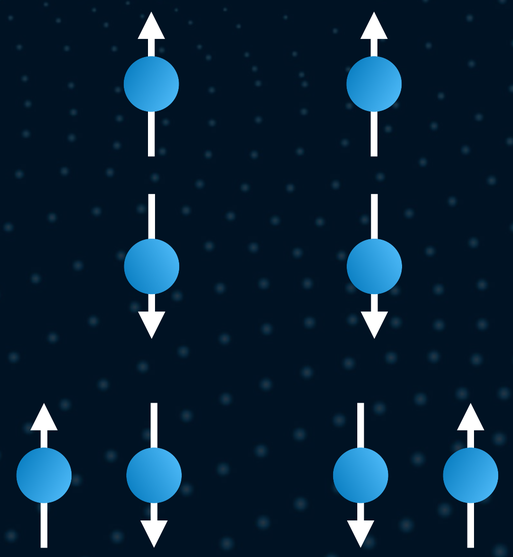
$$p(A=1, B=1) = |\langle 1_A 1_B | \psi\rangle|^2 = \frac{1}{2}$$

$$p(A=0, B=1) = p(A=1, B=0) = 0$$



Finalmente…l'entanglement

anche noto come"strana azione a distanza" (cit. Einstein)

Finalmente…l'entanglement

anche noto come"strana azione a distanza" (cit. Einstein)

	Risultati di misura su A
Misura 1	0
Misura 2	0
Misura 3	1
Misura 4	0
Misura 3	1
Misura 4	1
⋮	

$0 \rightarrow 50\,\%$ $\quad$ $1 \rightarrow 50\,\%$

Finalmente…l'entanglement

anche noto come"strana azione a distanza" (cit. Einstein)

	Risultati di misura su A
Misura 1	0
Misura 2	0
Misura 3	1
Misura 4	0
Misura 3	1
Misura 4	1
⋮	
	$0 \to 50\,\%$ $\quad 1 \to 50\,\%$

	Risultati di misura su B
Misura 1	0
Misura 2	0
Misura 3	1
Misura 4	0
Misura 3	1
Misura 4	1
⋮	
	$0 \to 50\,\%$ $\quad 1 \to 50\,\%$

Finalmente…l'entanglement

anche noto come"strana azione a distanza" (cit. Einstein)

	Risultati di misura su A		Risultati di misura su B
Misura 1	0	Misura 1	0
Misura 2	0	Misura 2	0
Misura 3	1	Misura 3	1
Misura 4	0	Misura 4	0
Misura 3	1	Misura 3	1
Misura 4	1	Misura 4	1
⋮			

Perfette correlazioni!

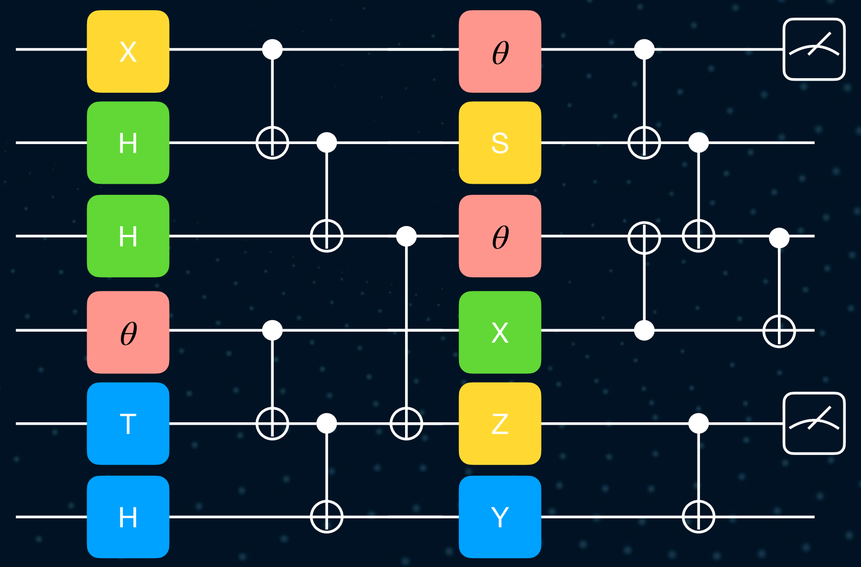
Circuiti quantistici

rappresentazione efficace di una computazione quantistica

$$|00\rangle \rightarrow H|0\rangle \otimes |0\rangle \rightarrow \text{CNOT}\big(H|0\rangle \otimes |0\rangle\big) = |\psi\rangle$$

1. Computazione inizia con tutti i qubit in $|0\rangle$
2. Si applica il gate Hadamard H sul primo qubit A
3. Si applica il gate CNOT con controllo su A e target su B

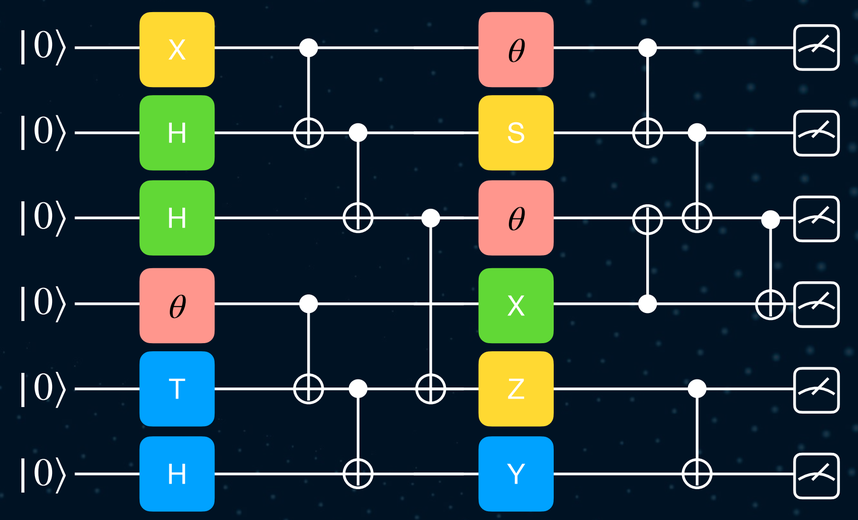
Esempio di circuito quantistico con più qubit



Algoritmi quantistici

la ricetta per una perfetta computazione quantistica

1. Sovrapposizione
2. Entanglement
3. Interferenza

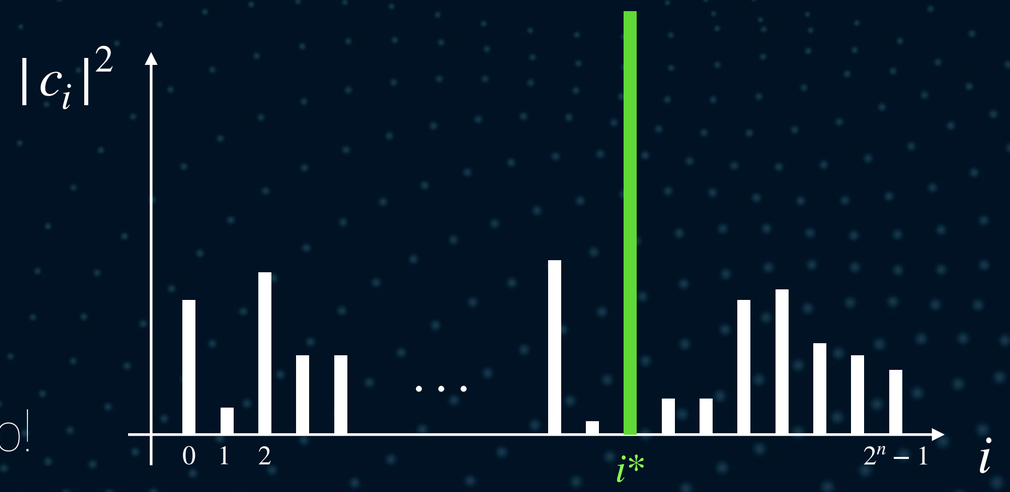


$$|\psi_0\rangle = |00\ldots0\rangle \rightarrow U_{QC}|\psi_0\rangle = |\psi_f\rangle = \sum_{i=0}^{2^n-1} c_i |i\rangle$$

Soluzione: $|i^*\rangle$

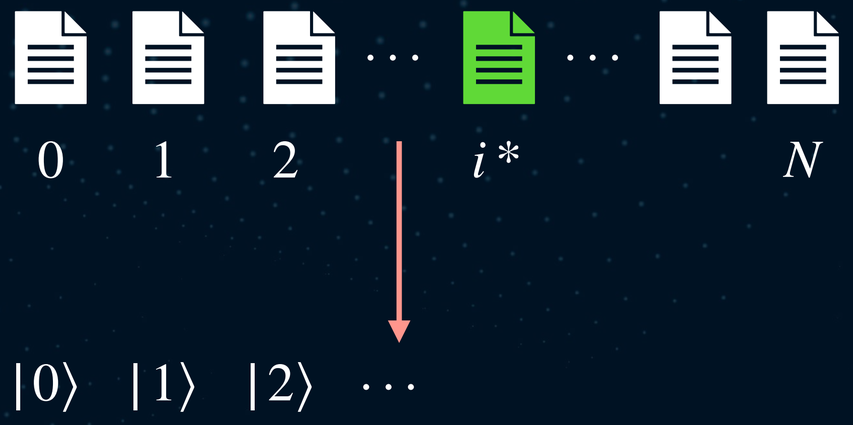
Se circuito/algoritmo tale che: $|c_{i^*}|^2 \gg |c_i|$

$\Longrightarrow$ alta probabilità di ottenere soluzione $|i^*\rangle$ quando misuriamo!

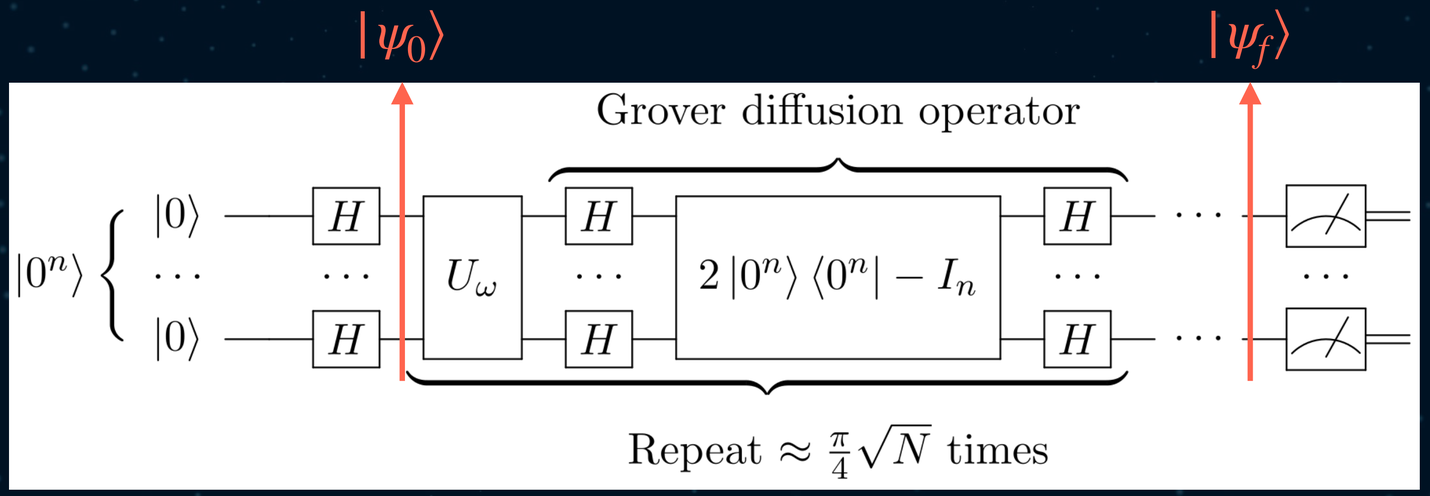


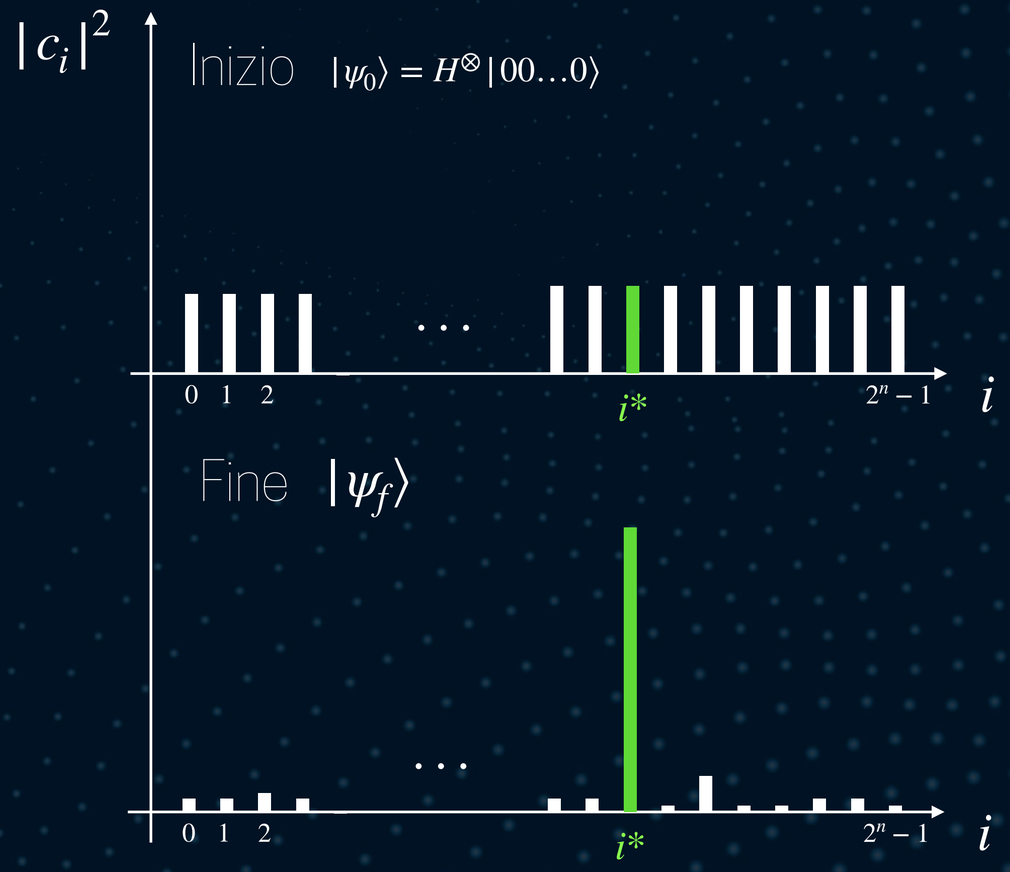
Algoritmo di Grover, revisited

ricerca in un database non strutturato



Classicamente servono $O(N)$ operazioni per trovare soluzione





Part II

Hands-on programmazione di un computer quantistico

(resto del tempo)

Quantum software

Quantum Circuits

Examples (i.e. noise)

Diverse librerie per quantum info/computing

python™

Qiskit IBM

Cirq Google

PENNYLANE XANADU

. . .

julia . . .

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Quantum Country — by Andy Matuschak and Michael Nielsen

A free introduction to quantum computing and quantum mechanics

By working through these essays, you will understand in detail all the basic principles of quantum computing and quantum mechanics, plus two important applications: the quantum search algorithm and quantum teleportation.

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Quantum computing for the very curious

How the quantum search algorithm works

How quantum teleportation works

Quantum mechanics distilled

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Community Italiana sulle tecnologie quantistiche

Unitevi al gruppo telegram dal sito:
https://www.bequantum.it/

Let’s code now

Step 1:

Create un account su IBM Quantum
https://quantum.ibm.com/

Step 2:

Andate su:
https://github.com/stfnmangini/handsonqc_genova2025