

Quantum Computing

From algorithms to artificial intelligence:
challenges and promises of an emerging technology



UNIVERSITÀ DI PAVIA
Dipartimento di Fisica

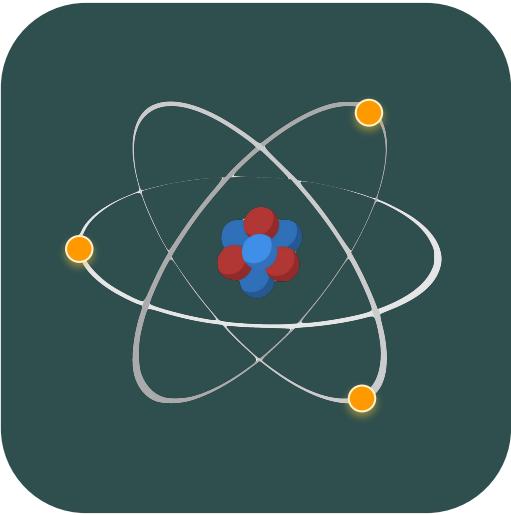
The Quantum Realm

? ? ? ? ?





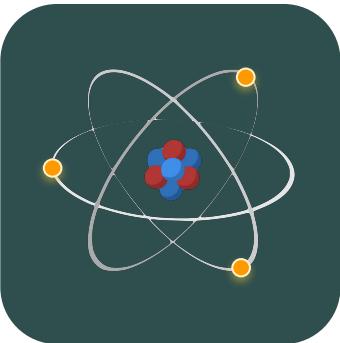
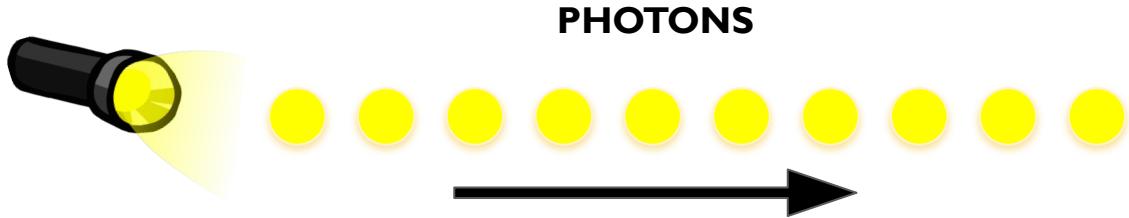
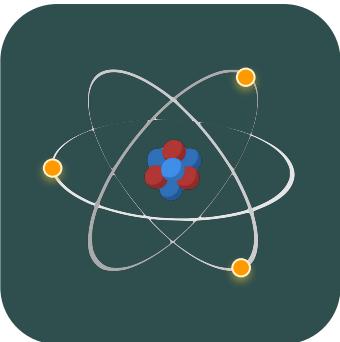
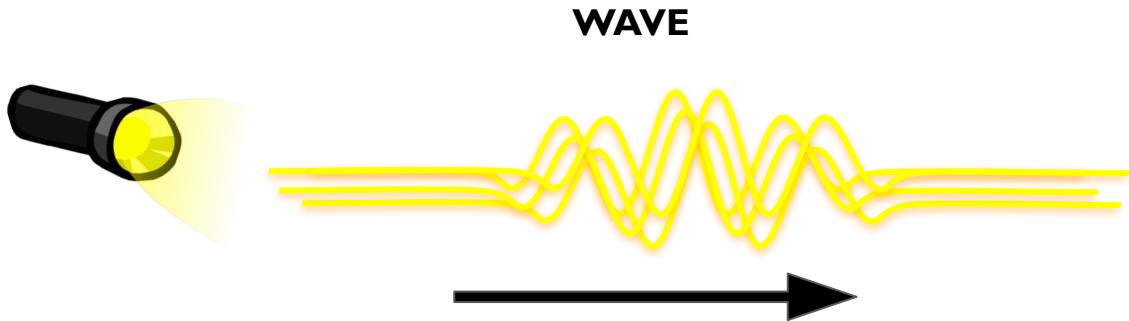
Quantum Mechanics



It describes phenomena at atomic and subatomic scale

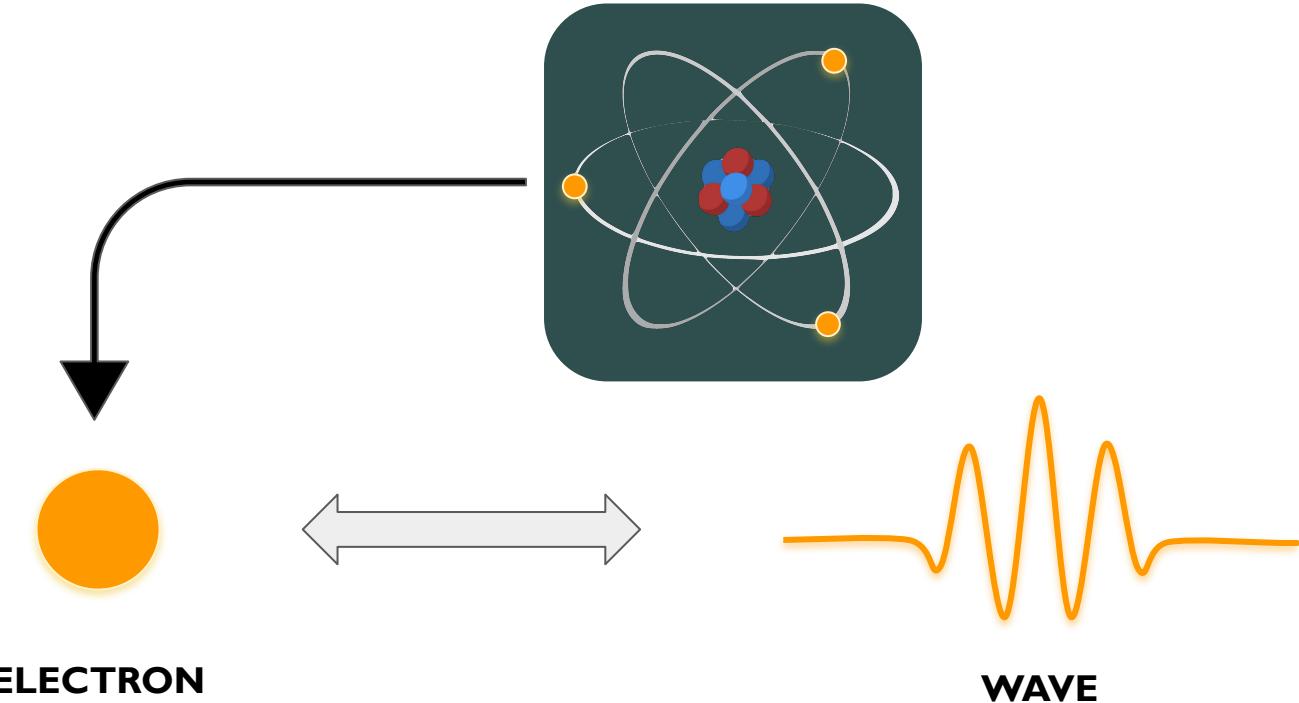


Quantum Mechanics





Quantum Mechanics

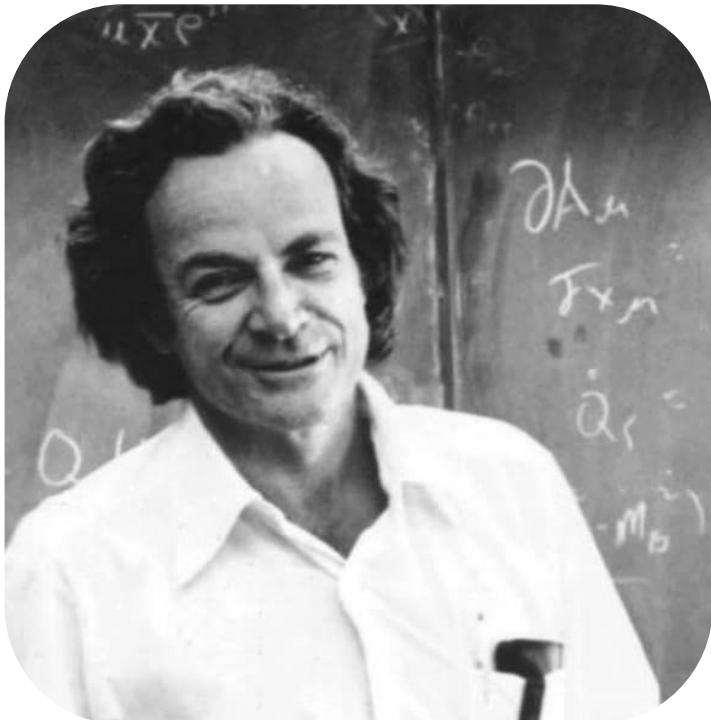


CONFUSED?





Understanding Quantum Mechanics



"If you think you understand quantum mechanics, you don't understand quantum mechanics."

Richard Feynman



First Quantum Computer proposal



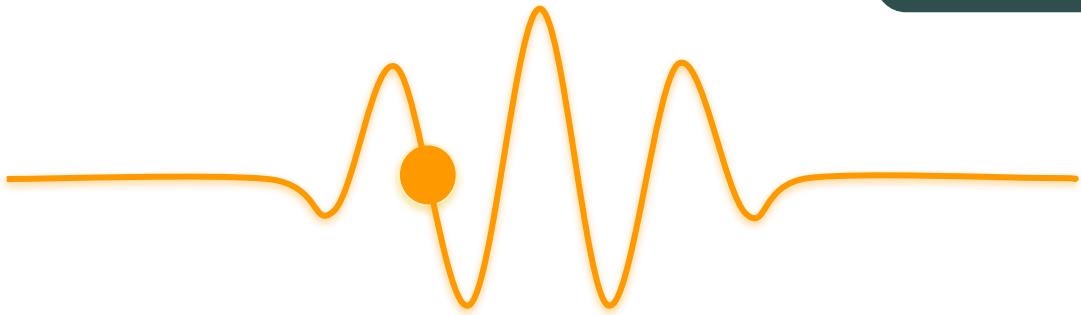
"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Richard Feynman



Quantum states

Wavefunction or QUANTUM STATE: $|\psi\rangle \rightarrow$ **VECTOR**

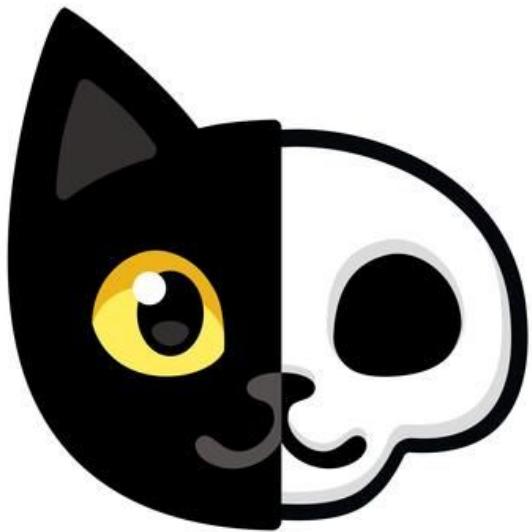


Quantum Properties of interest

Superposition

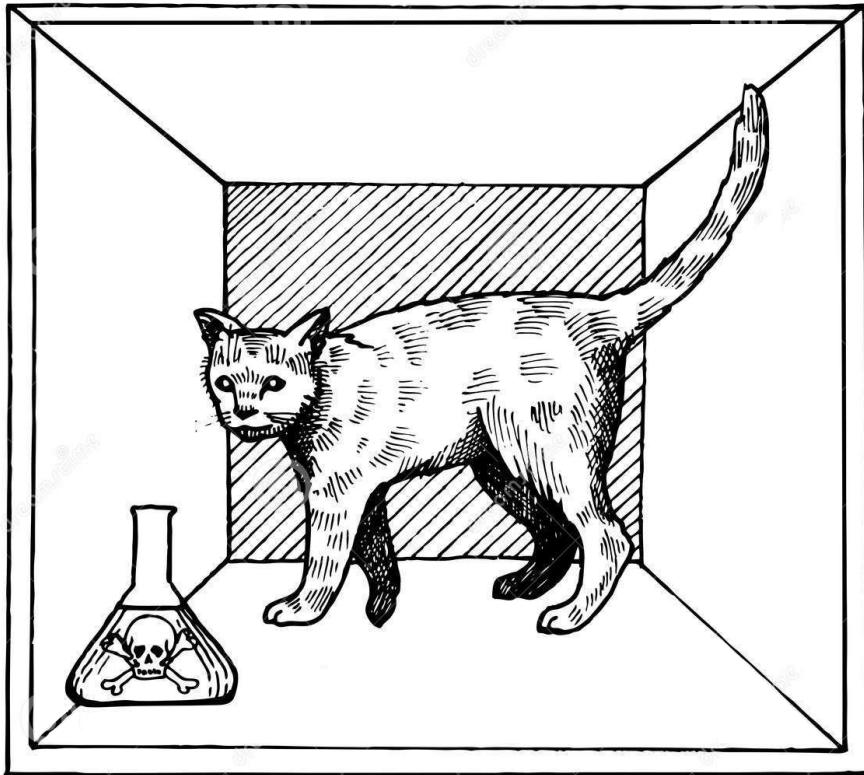
Entanglement

Superposition





Schrödinger's cat





Superposition

$$|\psi\rangle = a |\text{cat}\rangle + b |\text{skull}\rangle$$

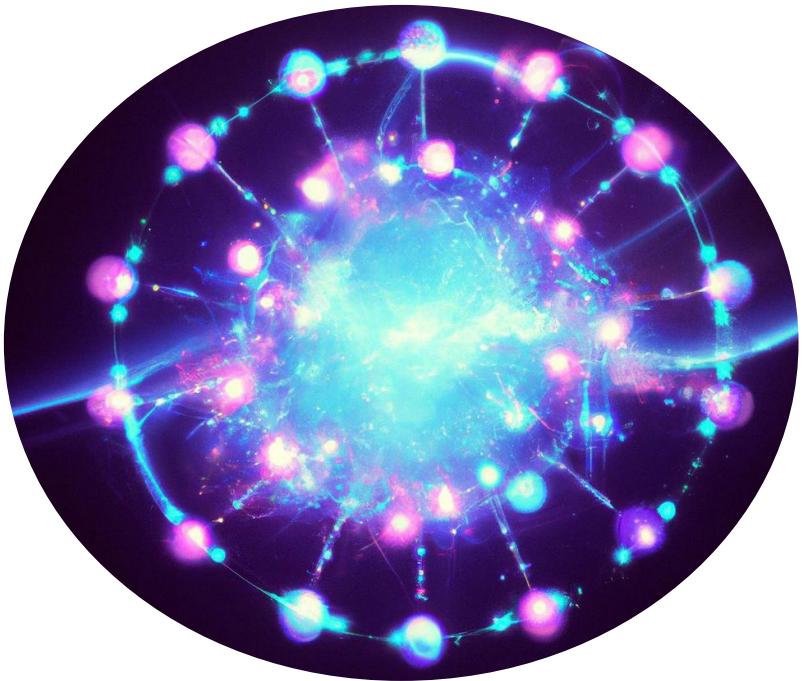
$$a, b \in \mathbb{C}$$

We get the state $|\text{cat}\rangle$ with probability $|a|^2$ and $|\text{skull}\rangle$ with probability $|b|^2$



Quantum Mechanics is a
PROBABILISTIC
theory

Entanglement

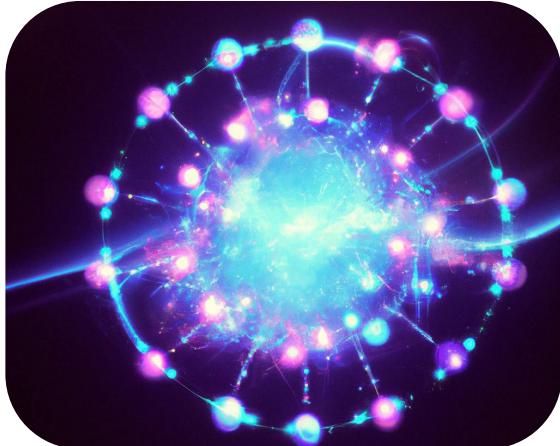
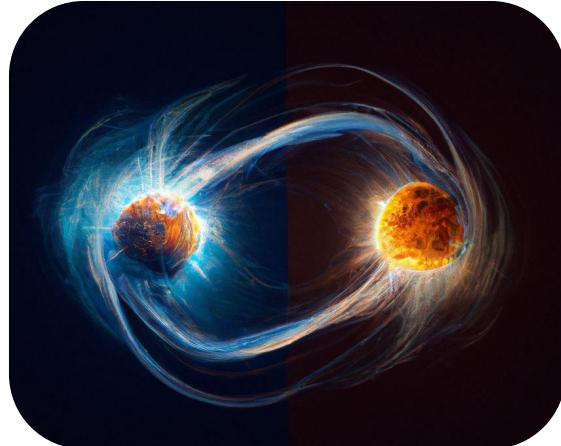




Entanglement

NON-CLASSICAL correlation

Systems have a unique wavefunction, we do not have SEPARATE states



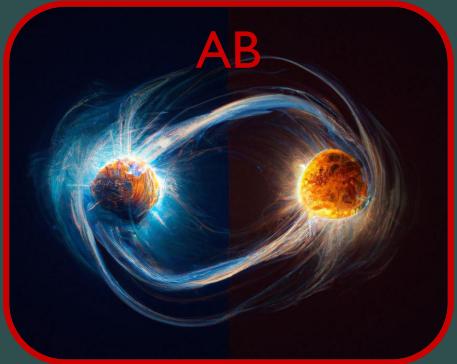


Entanglement

ENTANGLED STATES



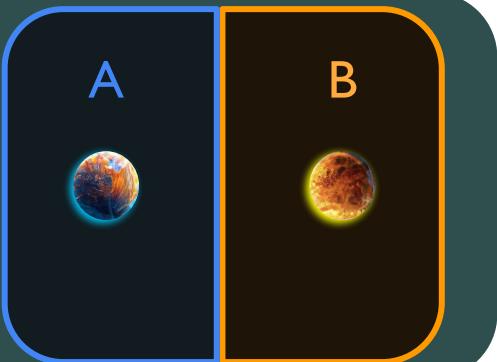
Systems have a unique wavefunction



SEPARABLE STATES



Systems can be described by separated
wavefunctions



Quantum Information

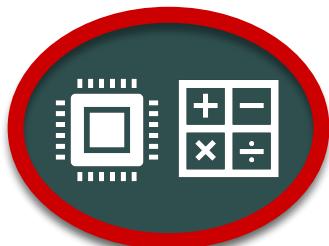




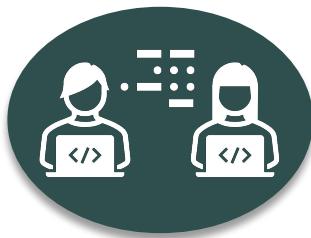
Quantum Information

“... the study of the information processing tasks that can be accomplished using quantum mechanical systems”

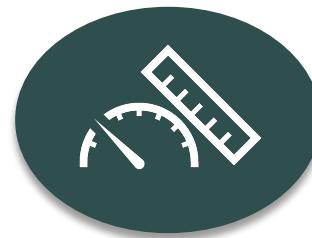
[Nielsen and Chuang “Quantum Computation and Quantum Information” (Cambridge 2010)]



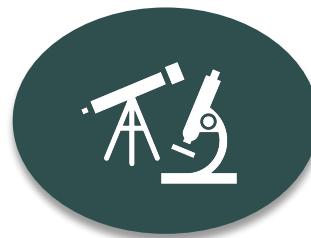
Computing



Communication
& Cryptography



Metrology



Imaging

AND OTHERS...



Unit of information

BIT

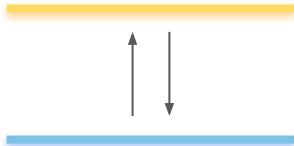


0

1

vs

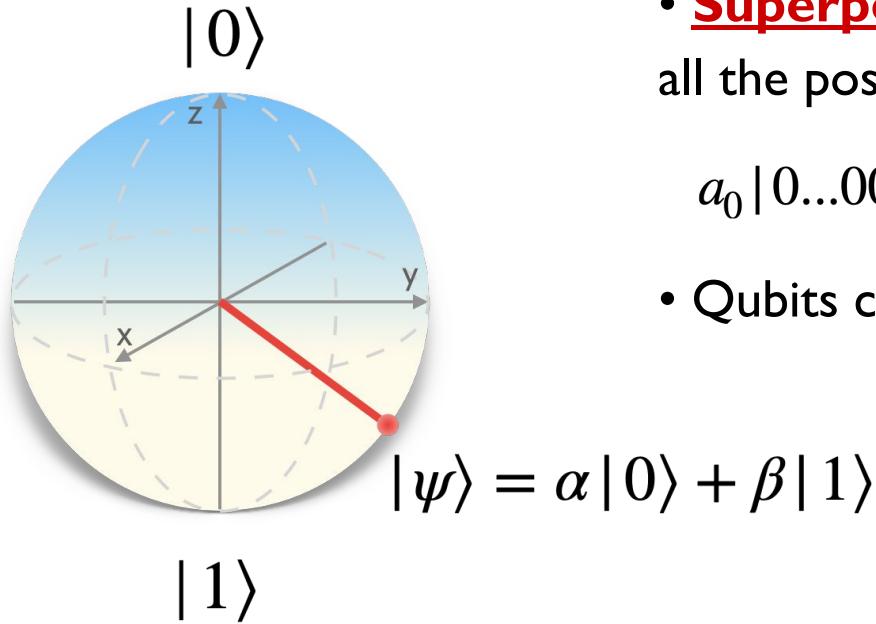
QUBIT



$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$
$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$



Quantum Bit



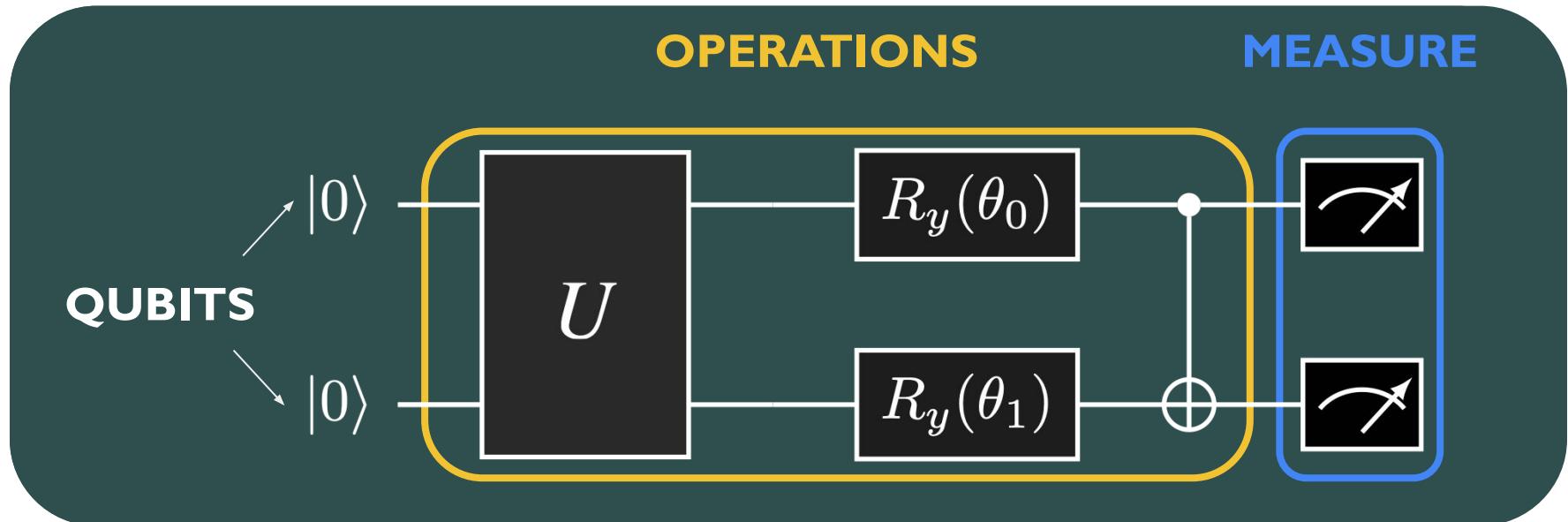
- **Superposition** allows to have all the possible bit strings simultaneously:

$$a_0|0\dots00\rangle + a_1|0\dots01\rangle + \dots + a_{2^n}|1\dots11\rangle$$

- Qubits can also share **entanglement**



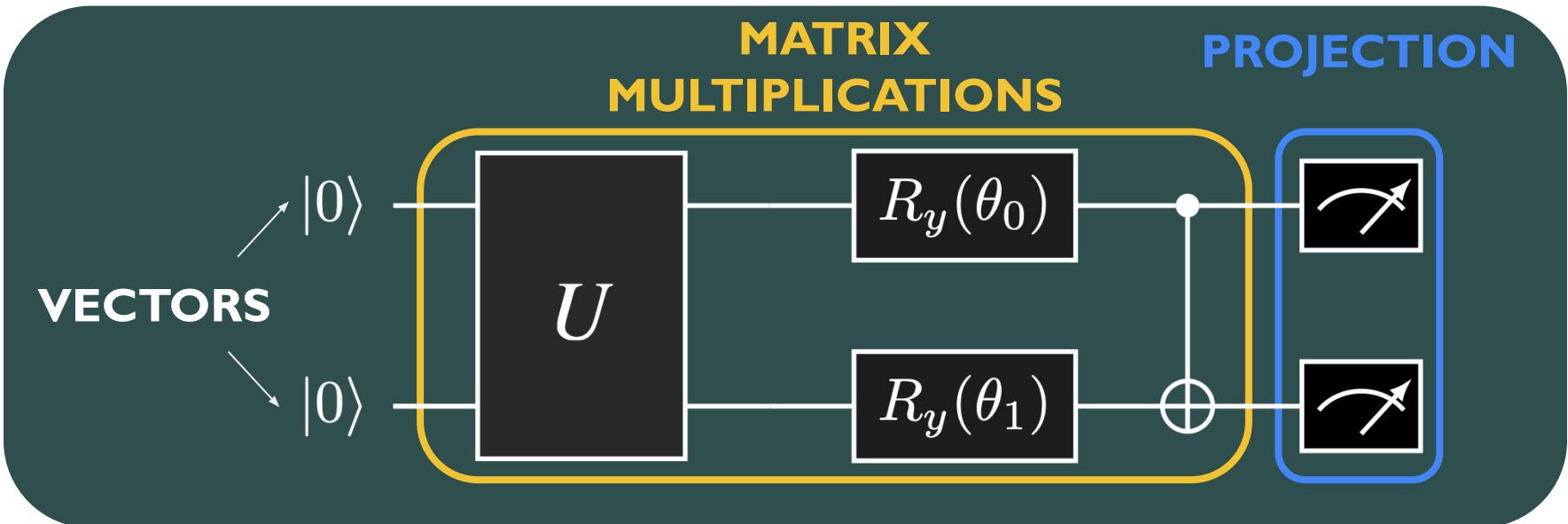
Circuital model



QM is **PROBABILISTIC** → The measurement needs to be repeated



How it works in practice?



IT'S LINEAR ALGEBRA!!





Quantum teleportation

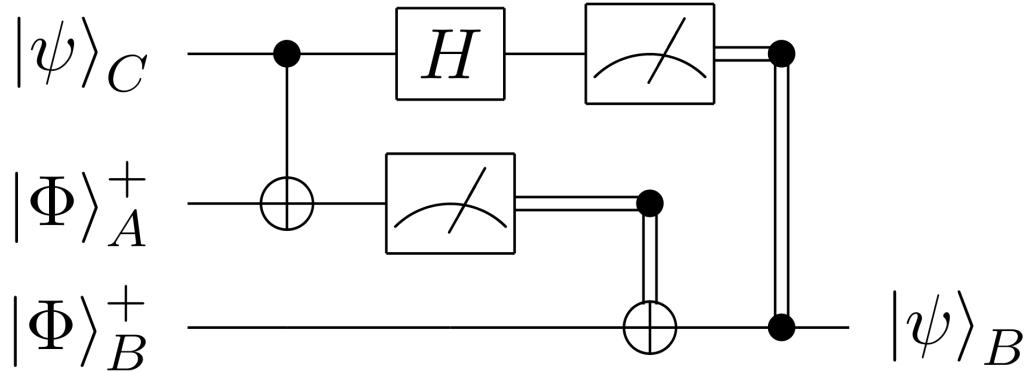


What we all
want!





Quantum teleportation



What we have!

Teleportation of a STATE between
two observers A and B by exchange
of classical bits

Earth-satellite
500-1400 km



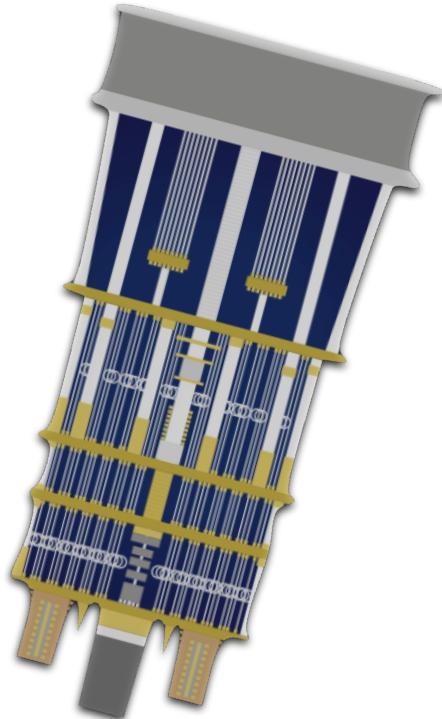
[Nature 549, 70–73 (2017)]



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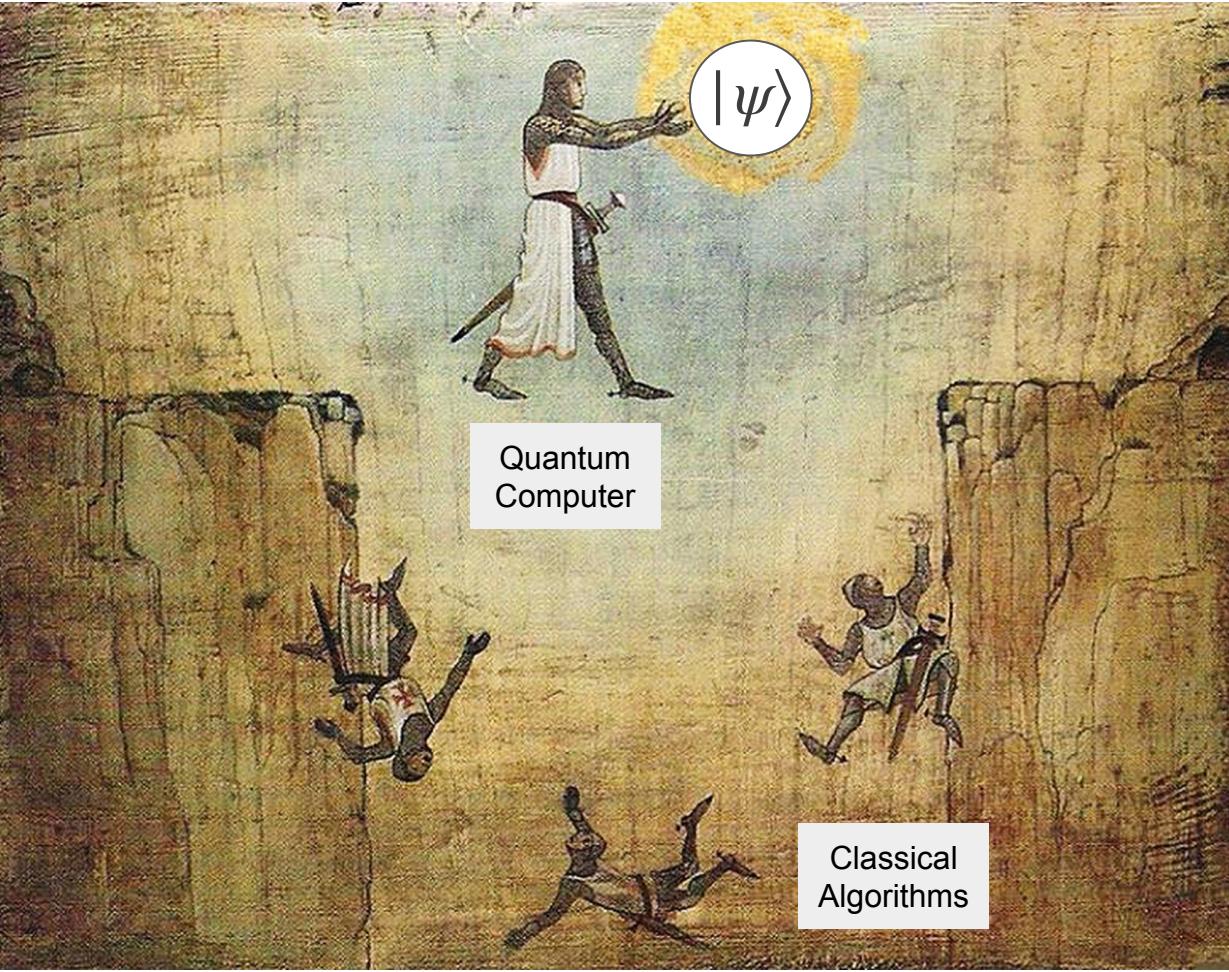


IN THE AGE OF
QUANTUM
COMPUTING



QUANTUM SUPREMACY

“Experts expect quantum computing to help us understand biology and evolution, cure cancer, and even take steps to reverse climate change” [Insider]

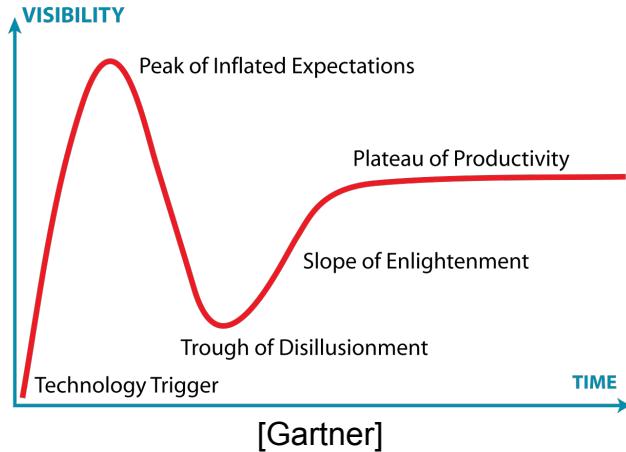


Quantum Computer

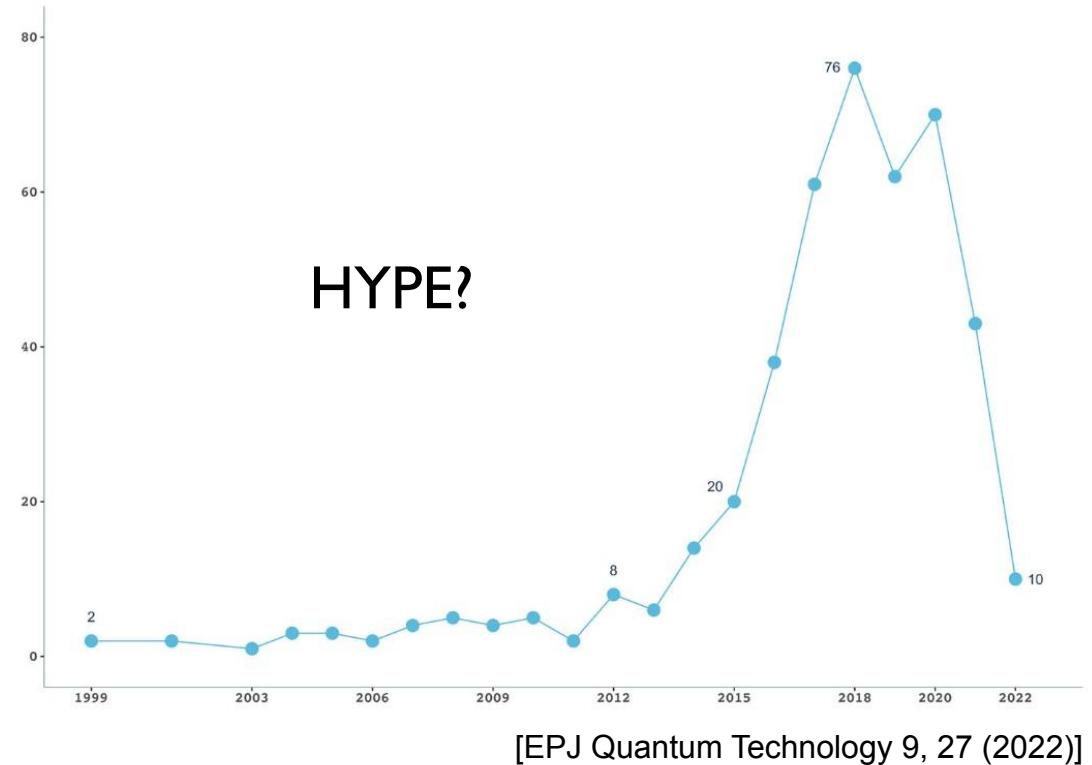
Classical
Algorithms

“The quantum computing market is projected to reach \$64.98 billion by 2030 from just \$507.1 million in 2019”

[P&S Intelligence]



Number of new quantum startups per year





the world on **Quantum.**

and many more...



What is the goal



Solving a task with less resources
than a classical computer

QUANTUM SUPREMACY?

QUANTUM ADVANTAGE



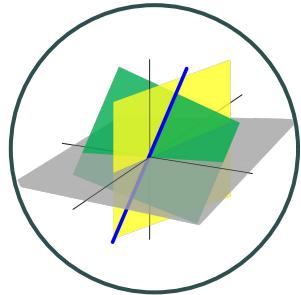
Superposition

Entanglement

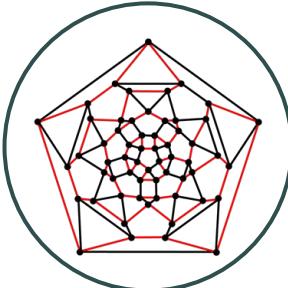




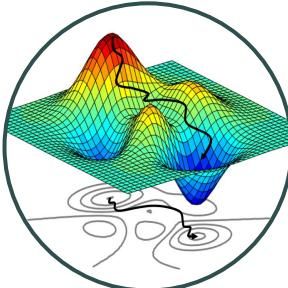
Applications of quantum computing



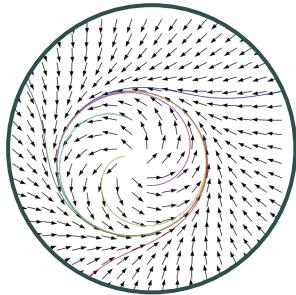
LINEAR ALGEBRA



COMBINATORICS



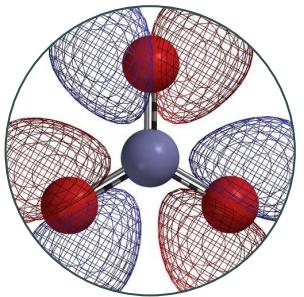
OPTIMIZATION



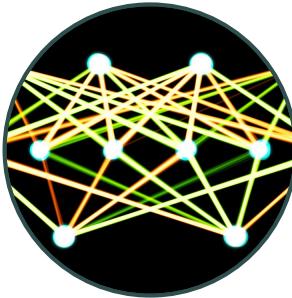
DIFFERENTIAL
EQUATIONS



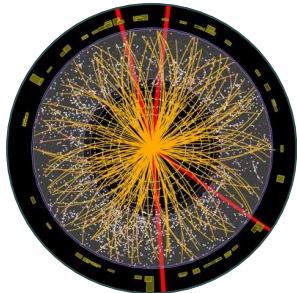
Applications of quantum computing



QUANTUM
CHEMISTRY



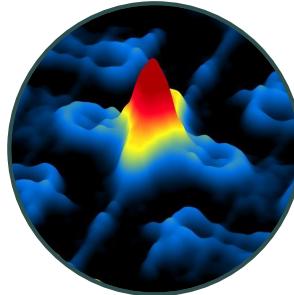
MACHINE
LEARNING



HIGH ENERGY
PHYSICS



FINANCE



PHYSICS OF
MATTER

AND OTHERS...



Bernstein-Vazirani algorithm

$(x_1, x_2, \dots, x_N) \rightarrow f \rightarrow \{0, 1\}$

Find s ?
 $f(x) = s \cdot x \bmod 2$

classicamente

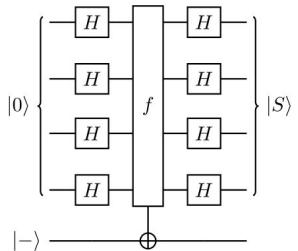
N queries



N input to find
 (s_1, s_2, \dots, s_N)

Bernstein-Vazirani

1 query



QUANTUM
ADVANTAGE!



Shor's algorithm

Integer number
factorization

Quantum advantage

classically
 \sim exponential



Shor
 $\log N$

IBM Q [Phys. Rev. A 100, 012305 (2019)]

[2001] $15 = 5 \times 3$



[2012] $21 = 7 \times 3$



[2019] $35 = 7 \times 5$

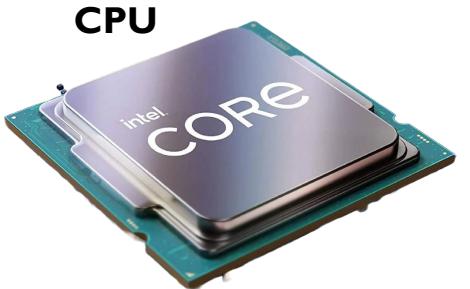


Why ??

Hardware faults...



Classical computational technologies



Electromagnetic
interaction to encode
and process the
information



CHANGE THE SCALE!

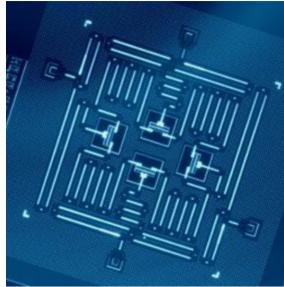


CLASSICAL SCALE

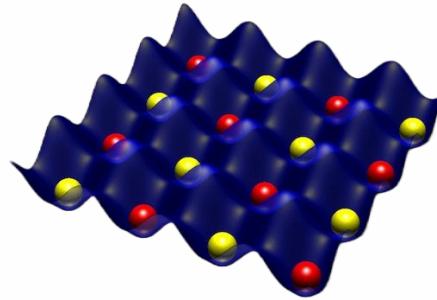


Quantum computational technologies

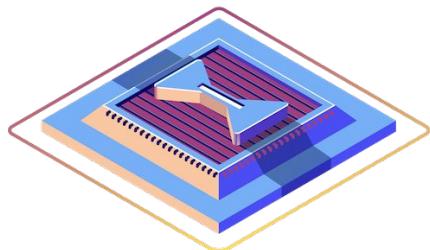
SUPERCONDUCTING CIRCUITS



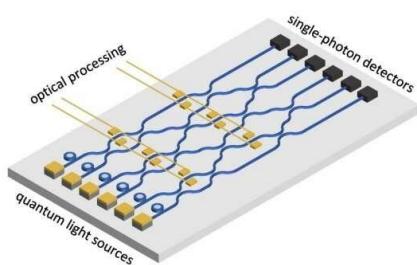
NEUTRAL ATOMS



TRAPPED IONS



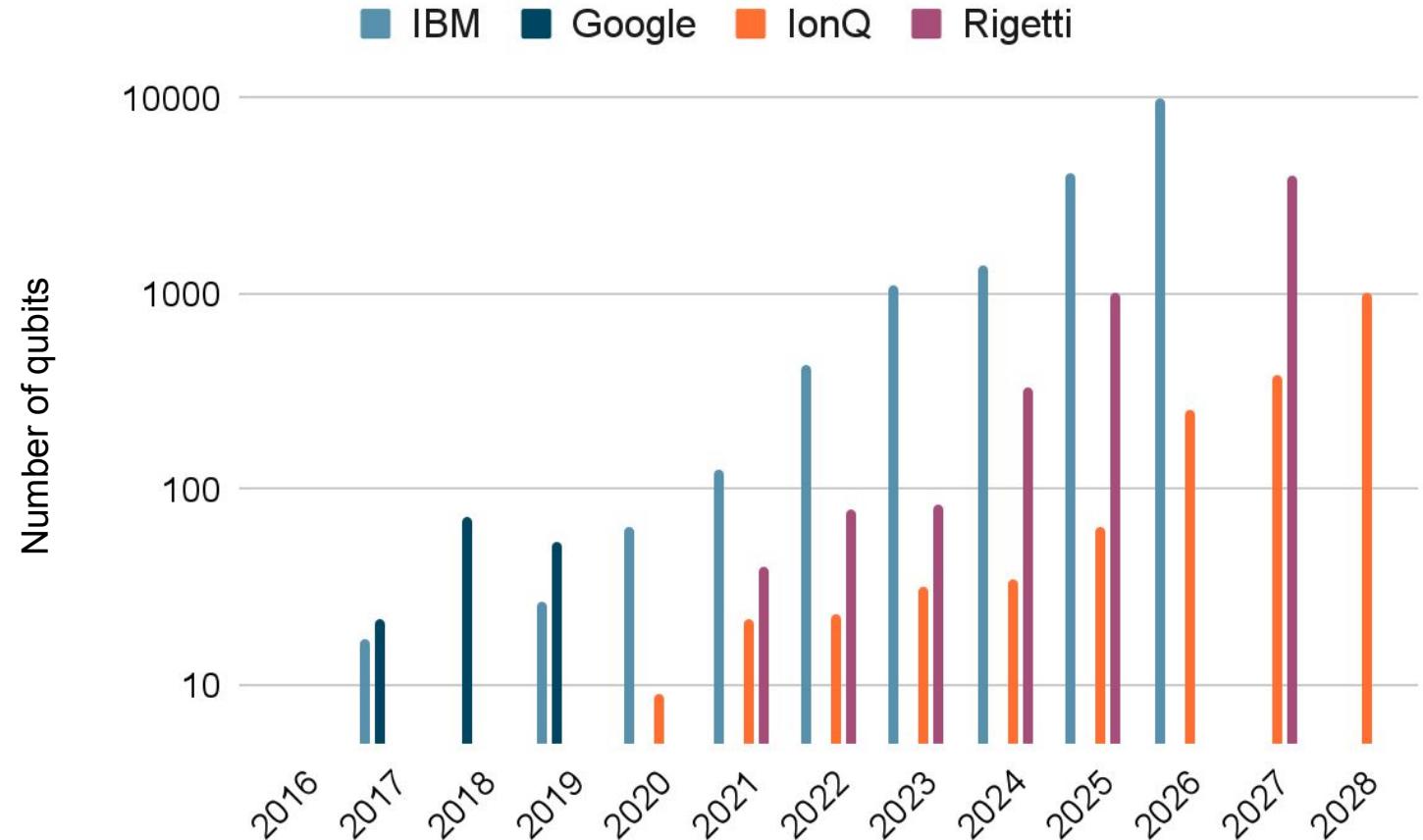
PHOTONS



AND OTHERS...



Roadmap

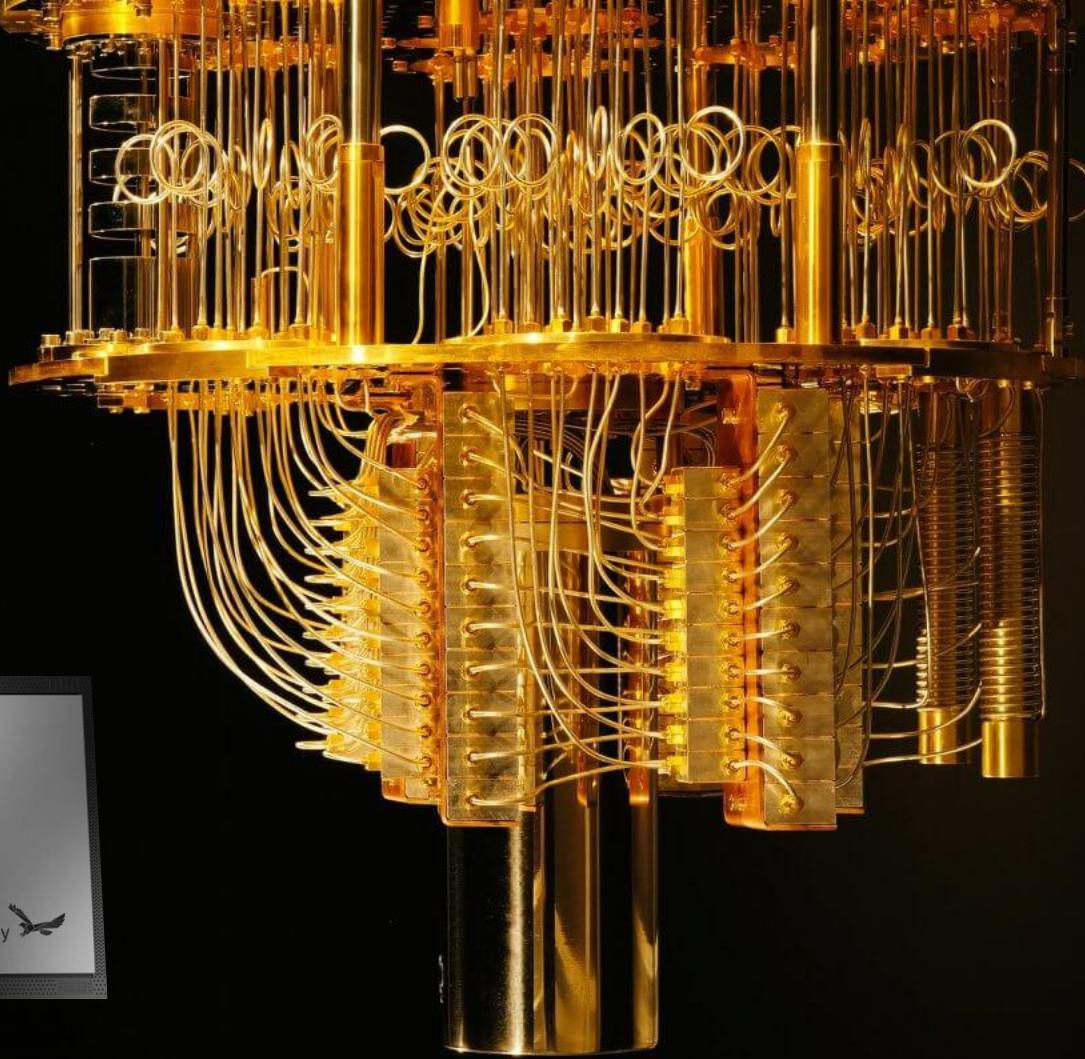
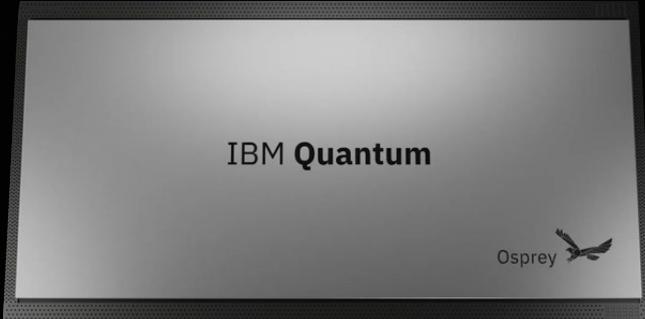




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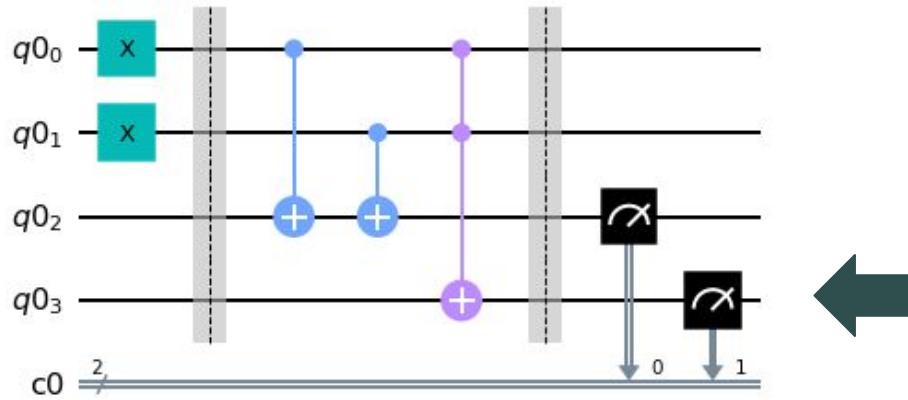


433 qubit





1+1 = ?

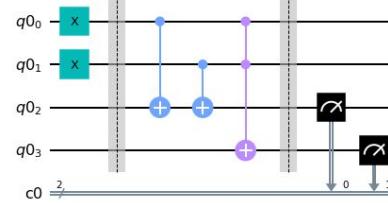
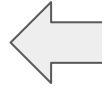
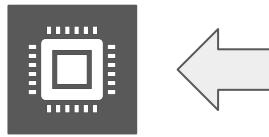
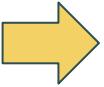


Quantum
half-adder

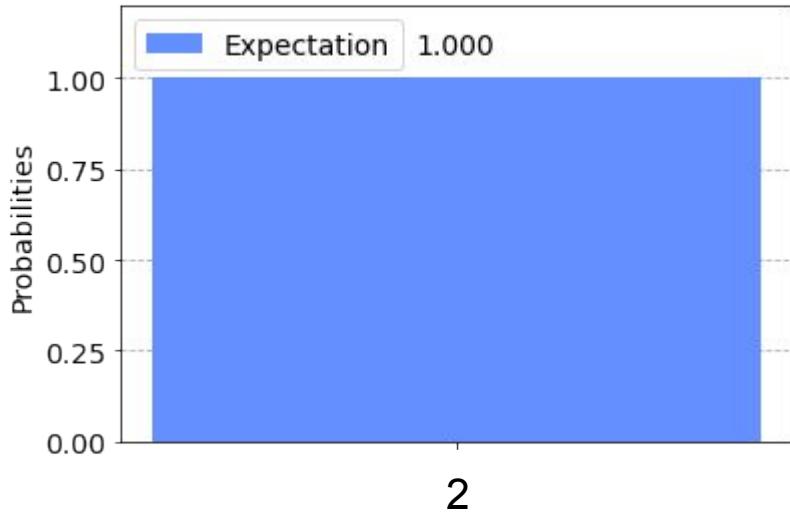
Truth table

| Input 1 | Input 2 | Output |
|---------|---------|--------|
| 0 | 0 | 0 (00) |
| 0 | 1 | 1 (01) |
| 1 | 0 | 1 (01) |
| 1 | 1 | 2 (10) |

Closed system

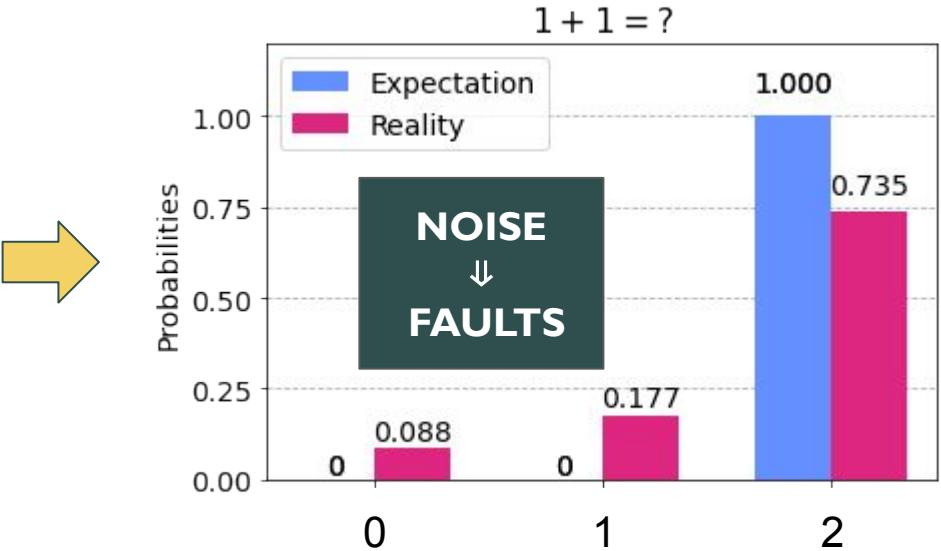
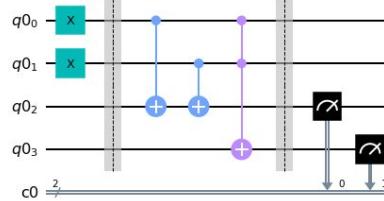
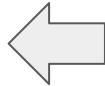
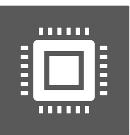
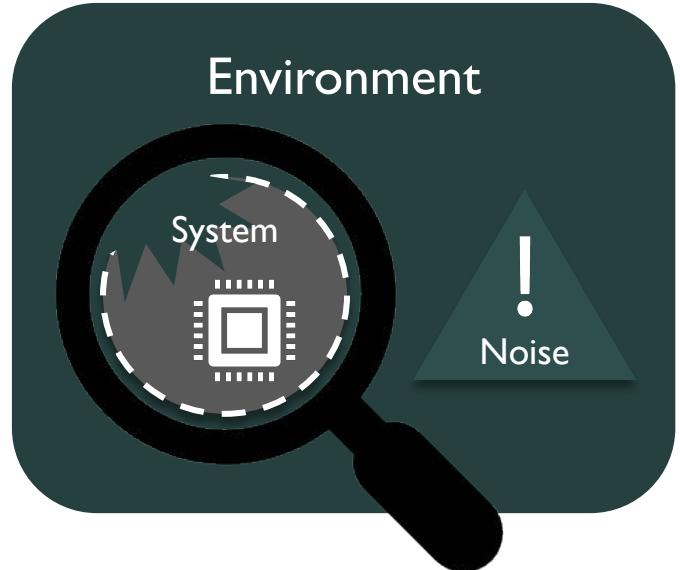


$$1 + 1 = ?$$



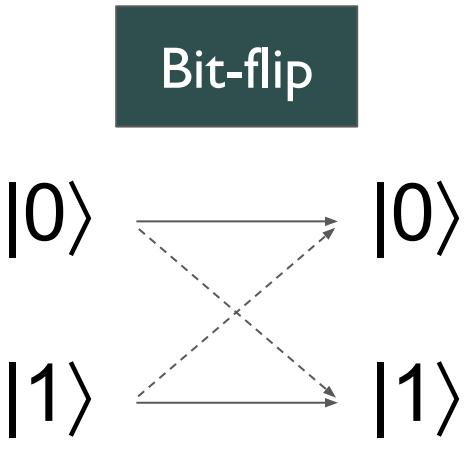
2

Open system

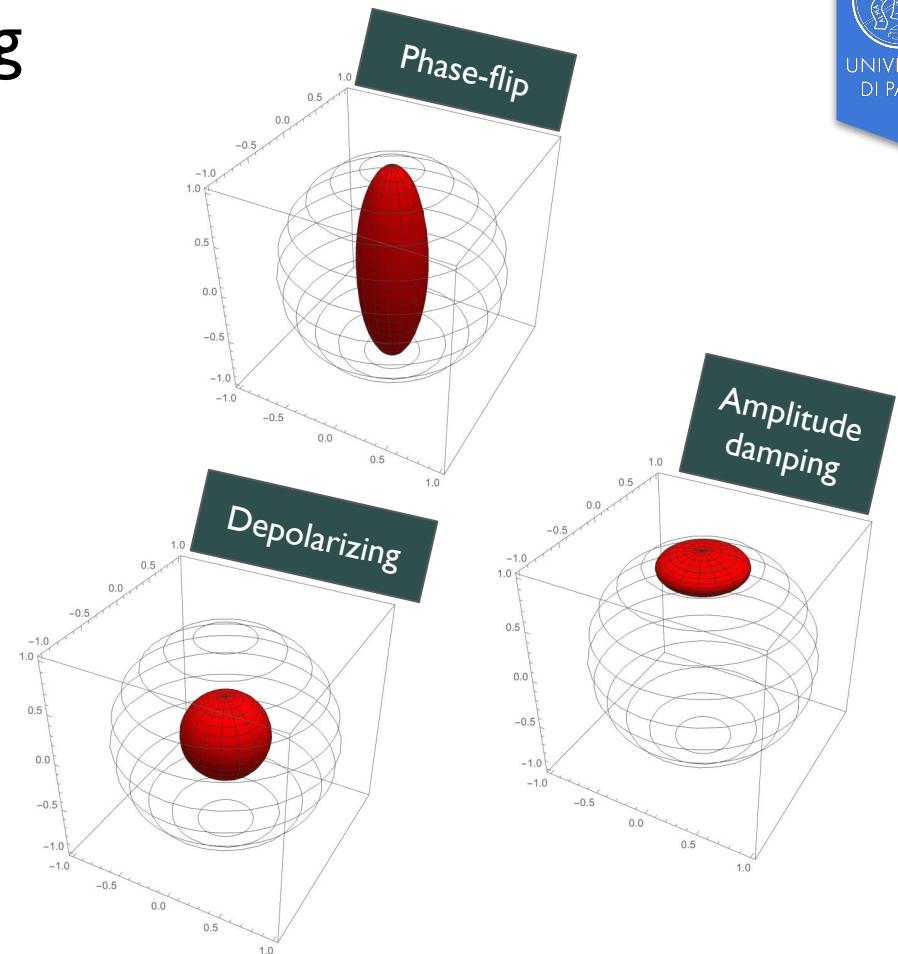




Noise in quantum computing



State inverted with a certain probability





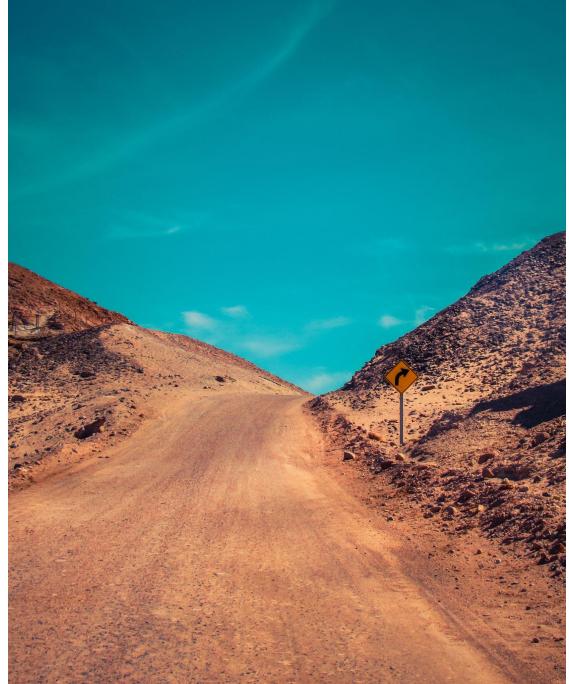
Noisy Intermediate-Scale Quantum Era (NISQ)



Expectation



Error-tolerant quantum
advantage

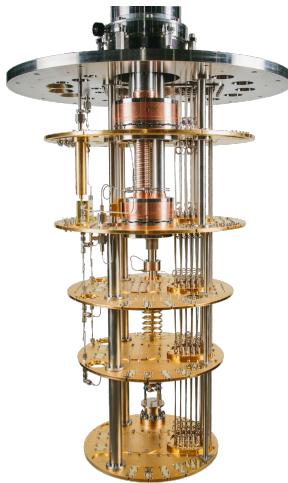
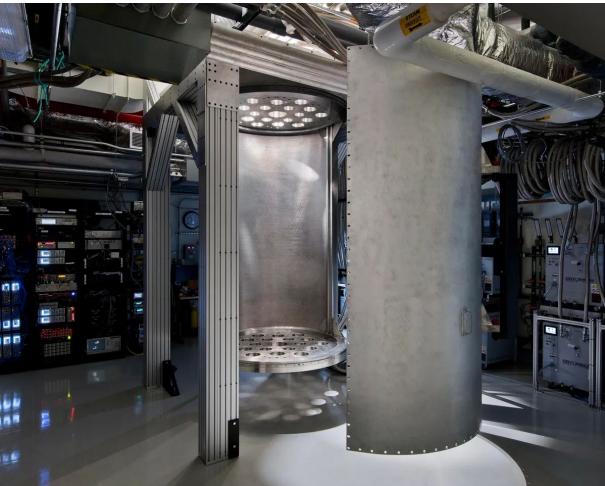


Reality



How to mitigate noise?

Hardware



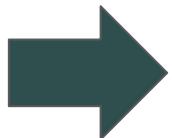


How to mitigate noise?

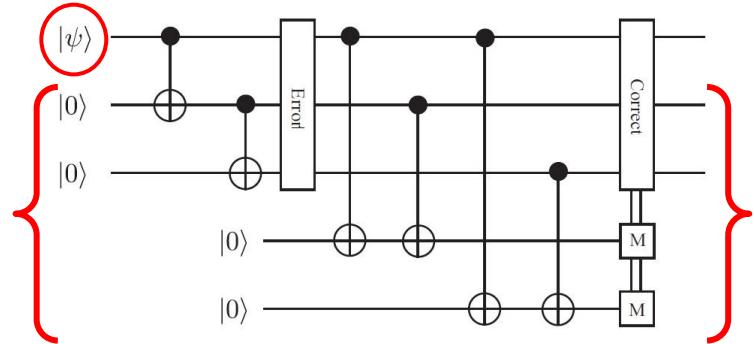
Software



Backup of
the state?



Quantum Error
Correction



- 🎯 “On-the-fly” correction
- ✖ Number of qubits increases



How to mitigate noise?

Software



Noise
Deconvolution



Post-processing
noise mitigation

$$\langle O \rangle_{\mathcal{N}(\rho)} = \rho \xrightarrow{\mathcal{N}_{\text{Pauli}}} \xrightarrow{O} \quad (a)$$

$$\langle O \rangle_{\rho} = \sum_{k=0}^{d^2-1} \frac{O_k}{\Gamma_{kk}} \times \rho \xrightarrow{\mathcal{N}_{\text{Pauli}}} \xrightarrow{\mathcal{P}_k} \quad (b)$$



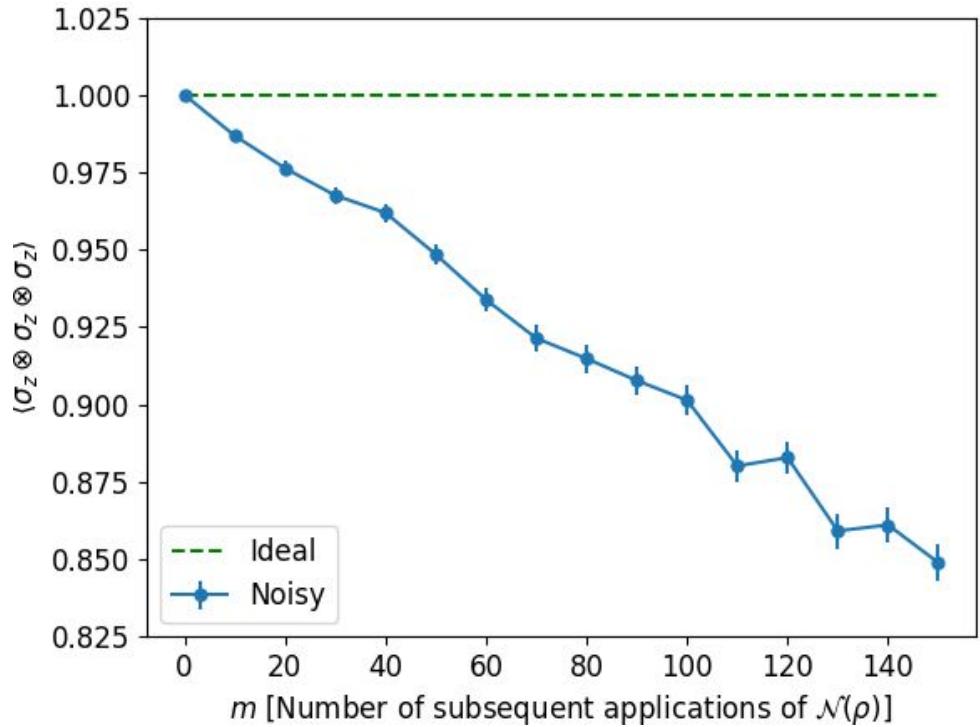
Correction at data analysis



Number of qubits does NOT change

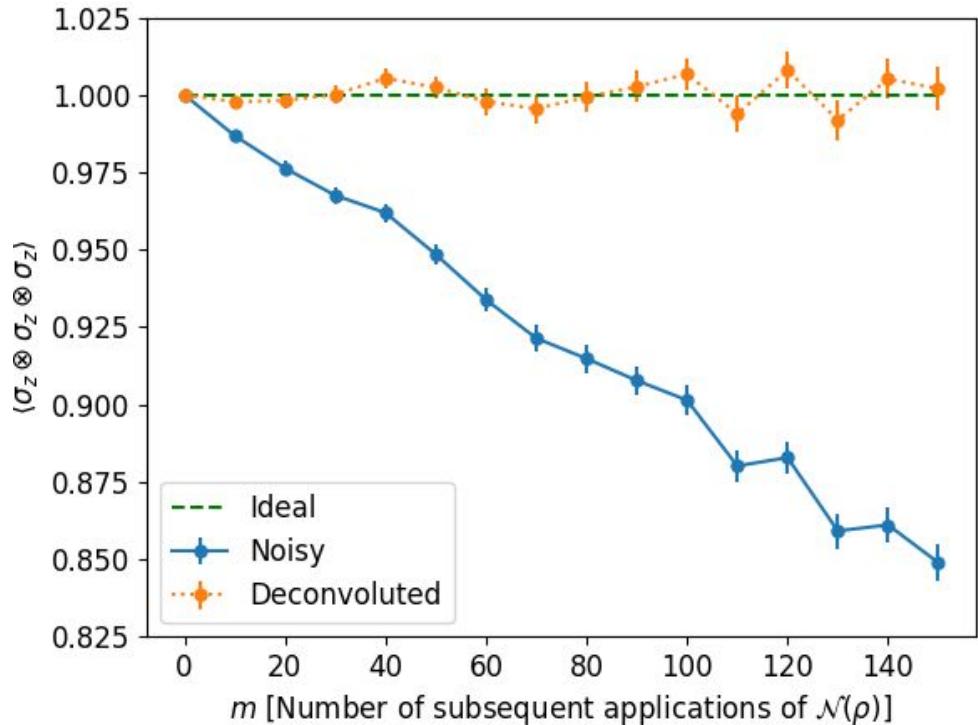


Noise Deconvolution





Noise Deconvolution

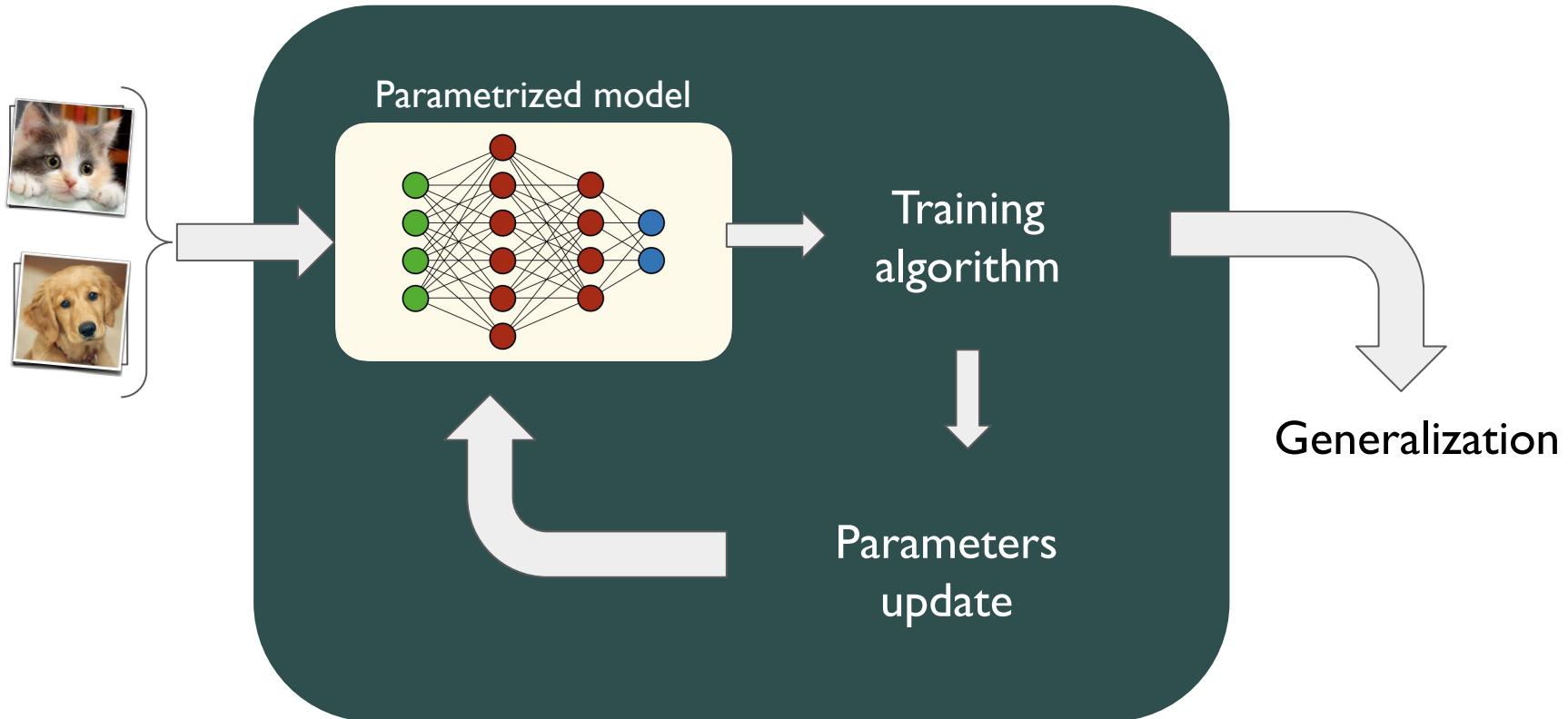


Machine Learning



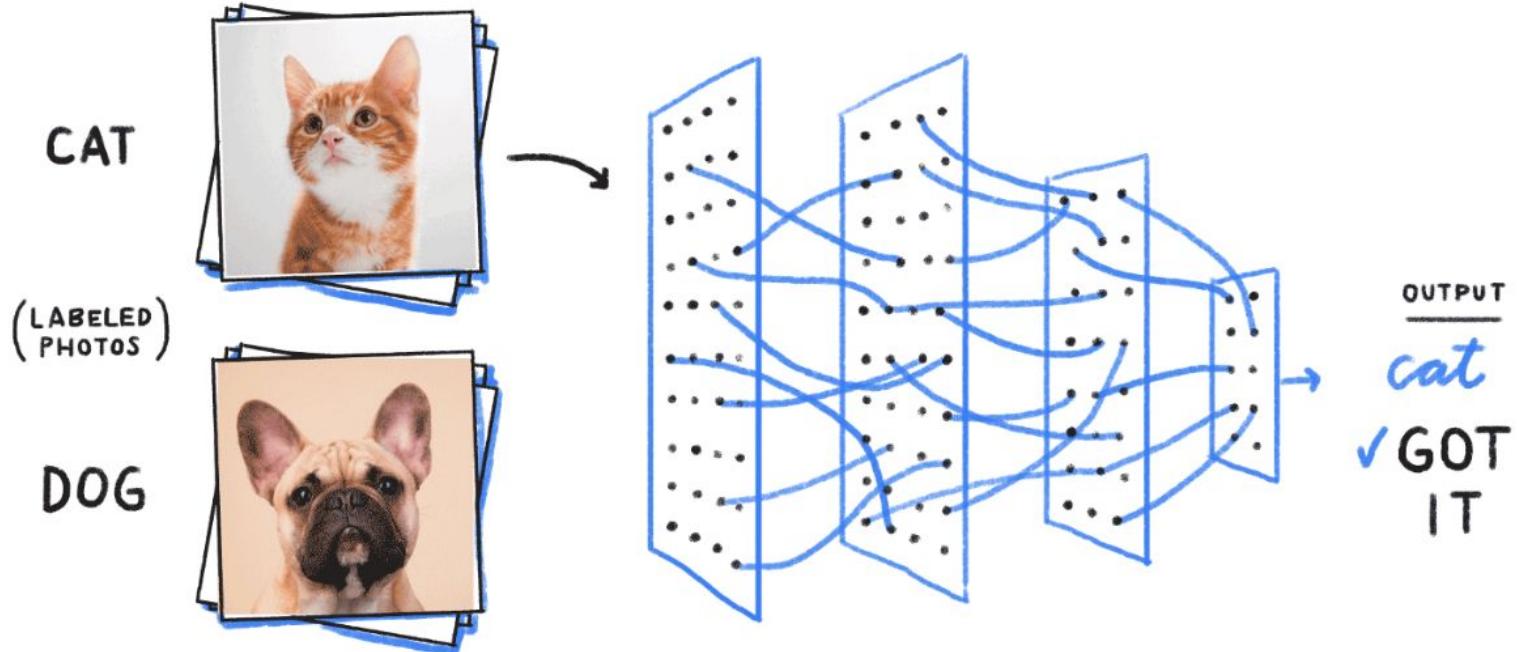


General scheme





Generalization



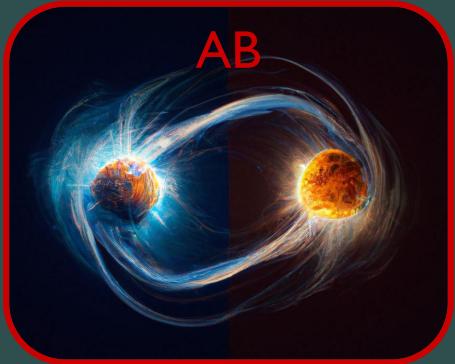


Entanglement

ENTANGLED STATES



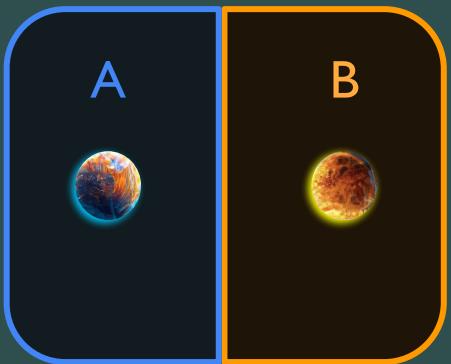
Systems have a unique wavefunction



SEPARABLE STATES



Systems can be described by separated
wavefunctions





Quantum states analysis with a Quantum Computer



"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



QUANTUM COMPUTING

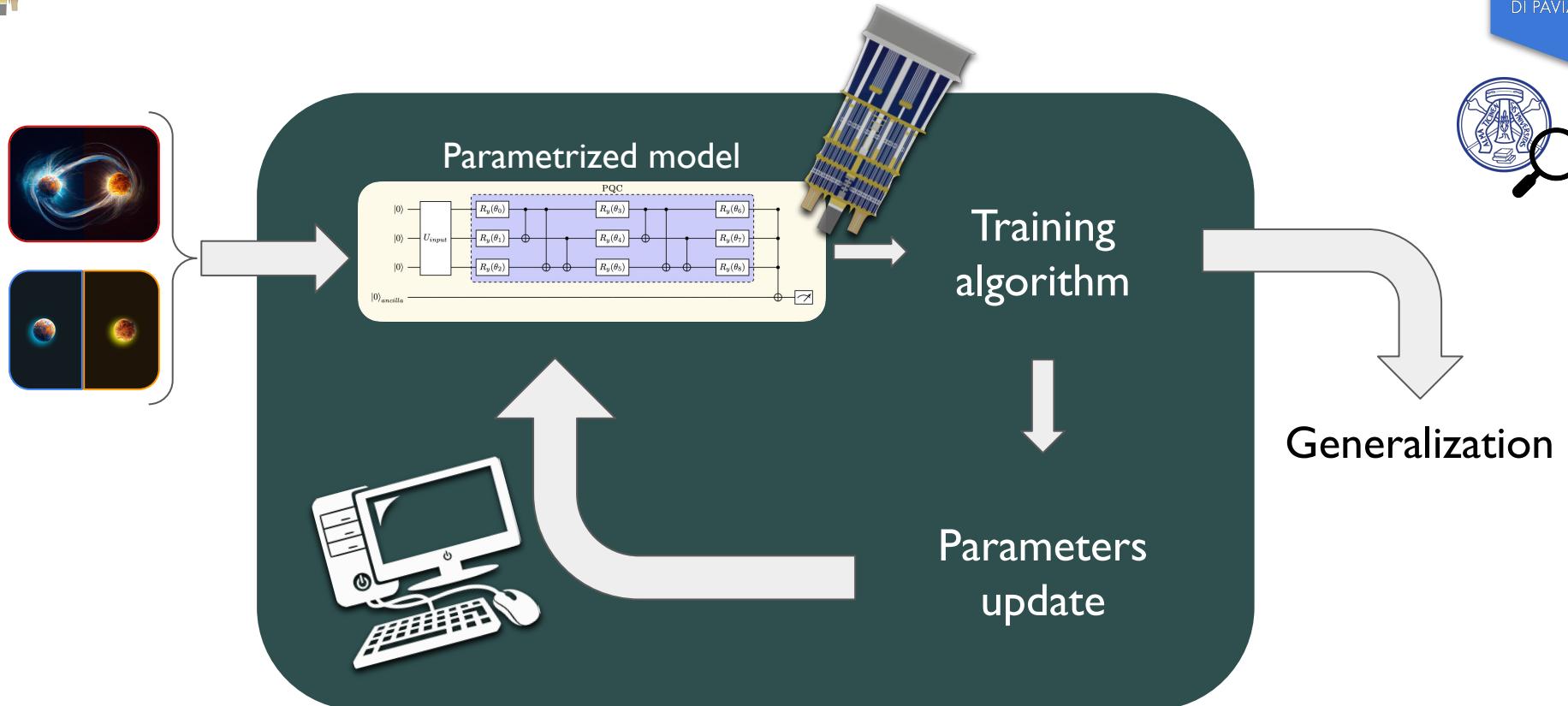
MACHINE LEARNING



QUANTUM MACHINE LEARNING



Distinguere stati quantistici





Take home message



- You can exploit quantum mechanics to do **computation**
- The goal is to obtain **QUANTUM ADVANTAGE**
- Current hardware is **NOISY**
- There are experimental and theoretical **techniques for reducing noise**
- You can combine Quantum Computing and Machine Learning (**QML**)
- An excellent application of QML can be the **analysis of quantum states**



Contacts

Quantum ML
e Photonics



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Quantum Noise -
Quantum Information e
Metrology



Simone Roncallo



Lorenzo Maccone



Chiara Macchiavello

simone.roncallo01@ateneopv.it



Useful resources

LEARNING



Qiskit



Qiskit | Quantum Explorers



**XANADU QUANTUM
CODEBOOK**



OTHERS



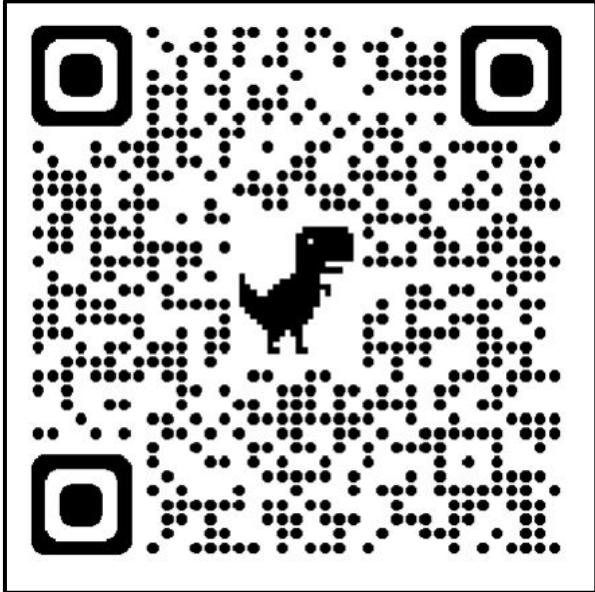
Unitary Fund



Quantum Computing Report
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<https://github.com/fran-scala/Quantum-computing-slides>