HDCRS Summer School

Introduction to Quantum Computing and its Ecosystem*

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1 June 2023

*with memes

CINECA QUANTUM COMPUTING LAB

CINECA Overview

- **CINECA** is a **Consortium** composed by **98 Italian universities and public institutions**.
- Since its origins in 1969, Cineca offers **support to scientific research**, **public** and **industrial**, through **supercomputing and the use of the most innovative computing systems based on state-of-the-art architectures and technologies**.
- **HPC Italian National Center**, owner of one of the most powerful supercomputer in Europe and the World

CINECA Overview

Leonardo: Cineca pre-exascale supercomputer

Fourth most powerful supercomputers in the world

Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
4	**Leonardo** - BullSequana XH2000, Xeon Platinum 8358 32C 2.6GHz, NVIDIA A100 SXM4 64 GB, Quad-rail NVIDIA HDR100 Infiniband, Atos EuroHPC/CINECA	1,824,768	238.70	304.47	7,404

Quantum Computing @ CINECA

CINECA: Italian HPC center

CINECA Quantum Computing Lab:

- Support research Universities, Industries and QC startups

- Internship programs, Courses and Conference (HPCQC)

https://www.quantumcomputinglab.cineca.it

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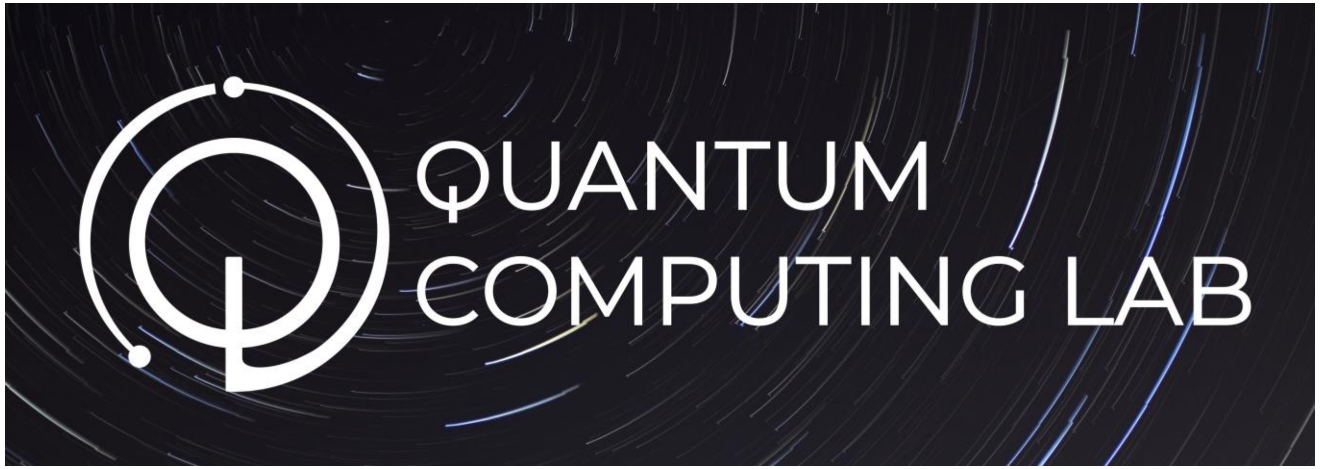
Linkedin



What is Quantum Computing?

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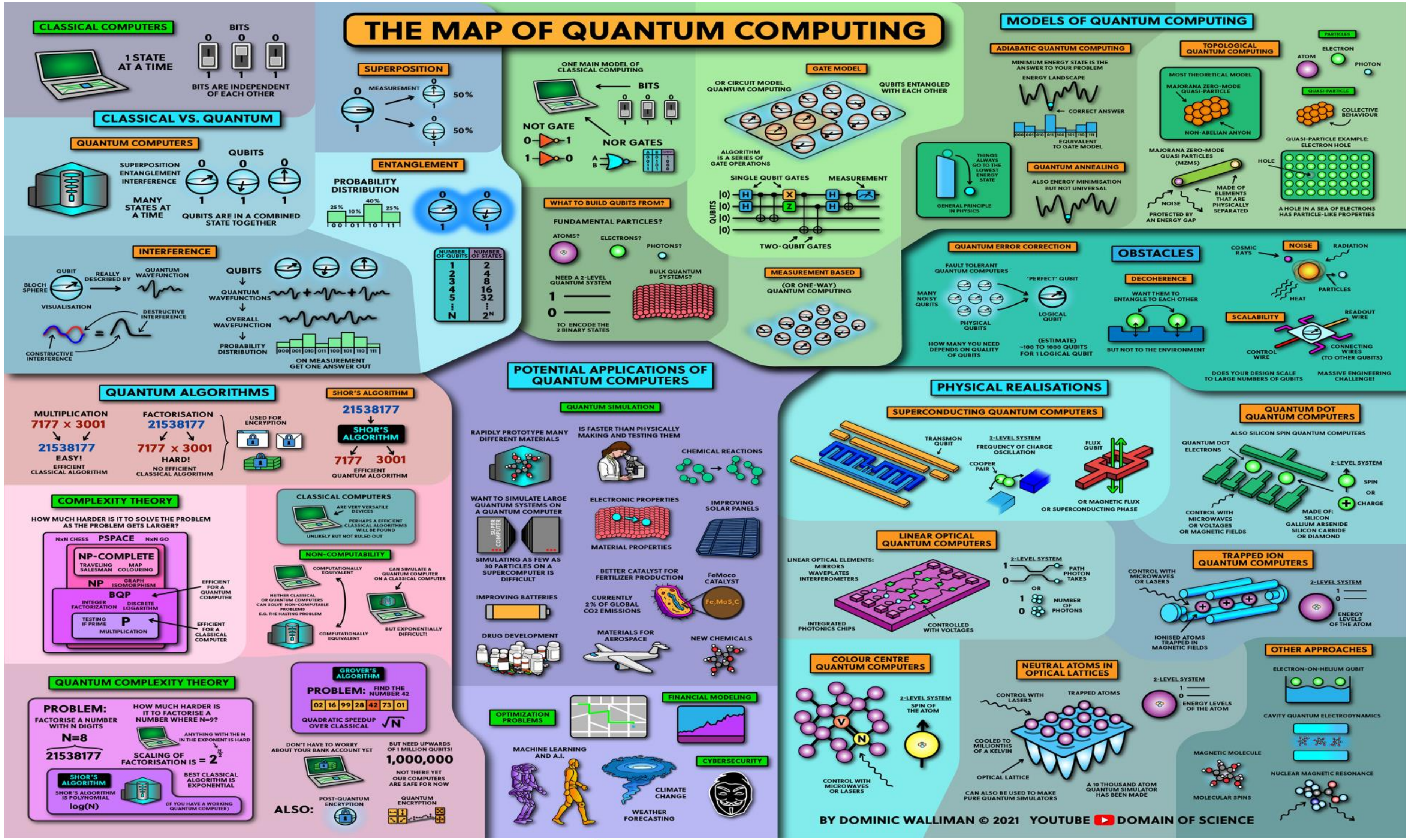


CINECA QUANTUM COMPUTING LAB

What is Quantum Computing?

A Quantum Computer <u>is NOT</u> simply a smaller or faster version of traditional computers or HPC systems

What is Quantum Computing?

A fundamentally new paradigm for information processing and computation

Based on the principles of Quantum Physics

Quantum Algorithms ≠ Classical Algorithms

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

Let’s take a step back.. What is Quantum Mechanics?

What is Quantum Mechanics?

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

Cit. Scott Aaronson

https://www.youtube.com/watch?v=SczraSQE3MY

What is Quantum Mechanics?

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

Cit. Scott Aaronson

..also Linear algebra Involved

Vectors (ket)

$$|\psi\rangle = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_n \end{pmatrix}$$

$\psi_i \in \mathbb{C}$

Complex Number

Tensor Product

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

Dimension = n^2

Unitary Operators

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

Hermitian Operators

$$A = A^\dagger$$

Nielsen, M. A., & Chuang, I. L. (2011). *Quantum Computation and Quantum Information*

Postulates of Quantum Computing

1. Unit of Information

Classically

Unit of classical information is the bit

State of a bit:

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

Postulates of Quantum Computing (1)

Quantumly

To a closed quantum system is associated a space of states *H* which is a Hilbert space. The pure state of the system is then represented by a unit norm vector on such Hilbert space.

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

State of a qubit:

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

Postulates of Quantum Computing (1)

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

State of a qubit:

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

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

Postulates of Quantum Computing (1)

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

State of a qubit:

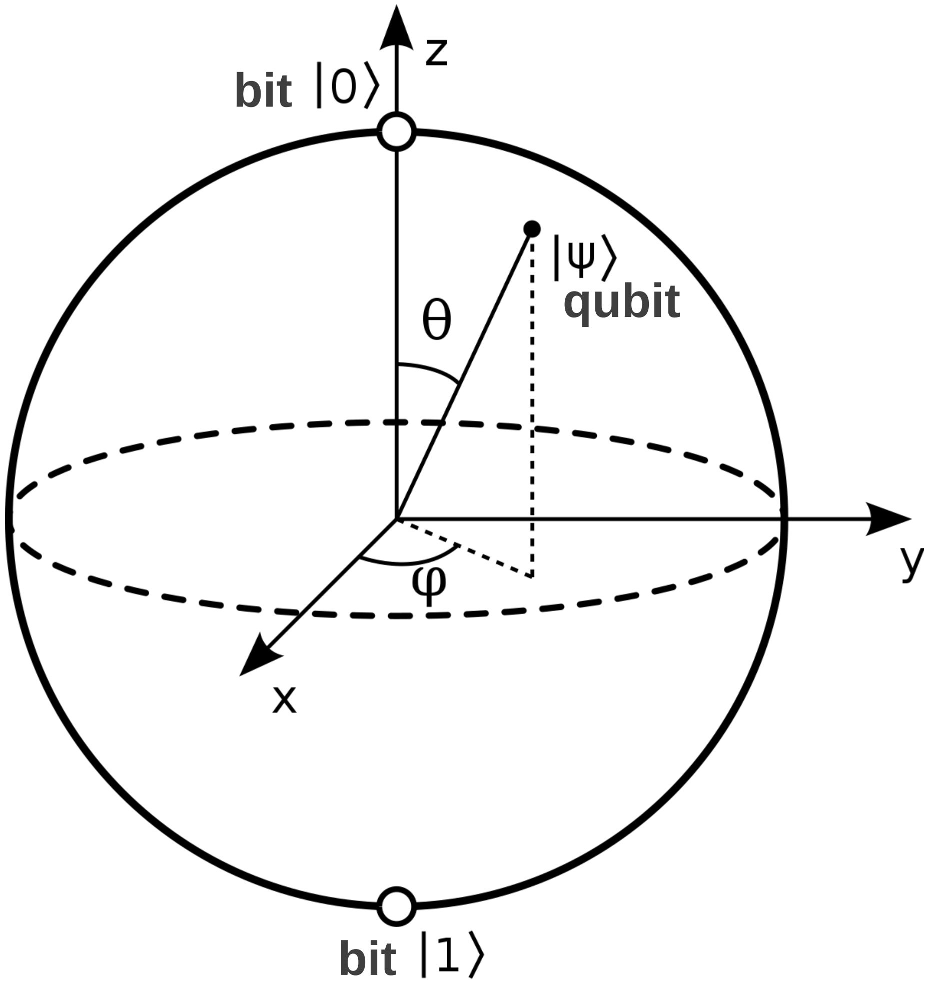
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

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

Can be parametrized as:

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

$$\theta \in [0, \pi] \qquad \phi \in [0, 2\pi]$$



2. Composite systems

Postulates of Quantum Computing (2)

Classically

State of N bits:

$$|000\ldots0\rangle, |100\ldots0\rangle, |010\ldots0\rangle \ldots |111\ldots1\rangle$$

Postulates of Quantum Computing (2)

Quantumly

The space of states of a composite system is the tensor product of the spaces of the subsystems

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

State of N qubits:

$$\alpha_1 |000..0\rangle + \alpha_2 |100..0\rangle + \alpha_3 |010..0\rangle + \dots \alpha_n |111..1\rangle$$

$$\alpha_i \in \mathbb{C} \qquad \sum_i |\alpha_i|^2 = 1$$

Quantum Entanglement

States that can be written as tensor product

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \dots \otimes |\psi_N\rangle$$

are called **factorable or product states**

Postulates of Quantum Computing (2)

Quantum Entanglement

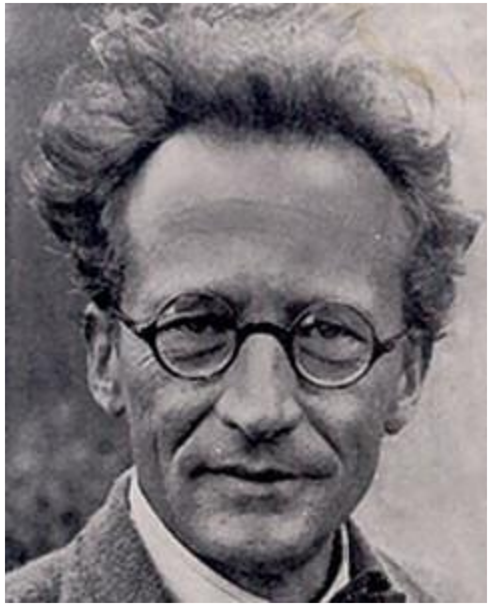
States that **can NOT** be written as tensor product

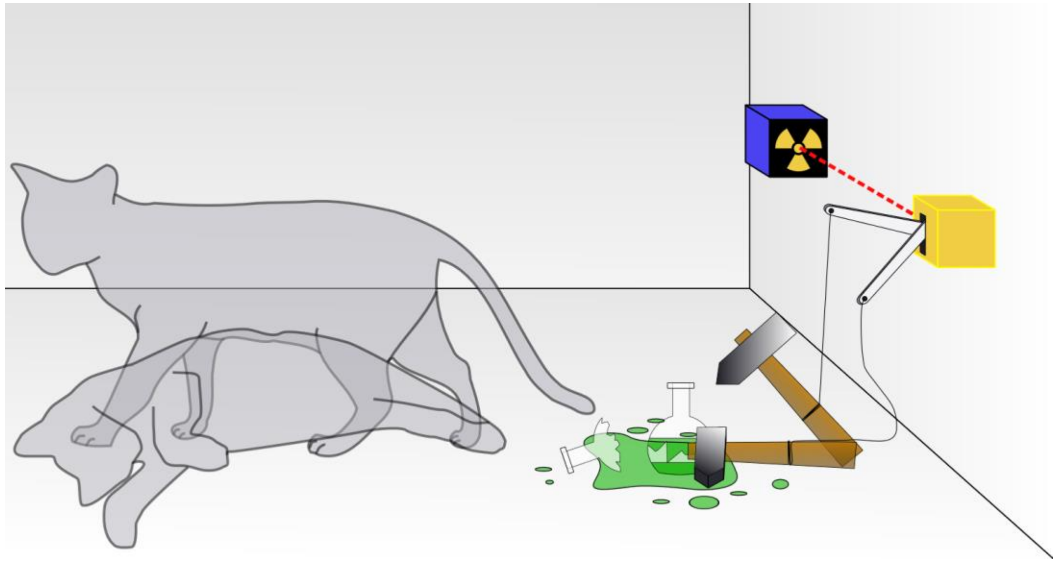
$$|\psi\rangle \neq |\psi_1\rangle \otimes |\psi_2\rangle \otimes \dots \otimes |\psi_N\rangle$$

are called **entangled states**

Quantum Entangled

Example: Schrödinger’s cat





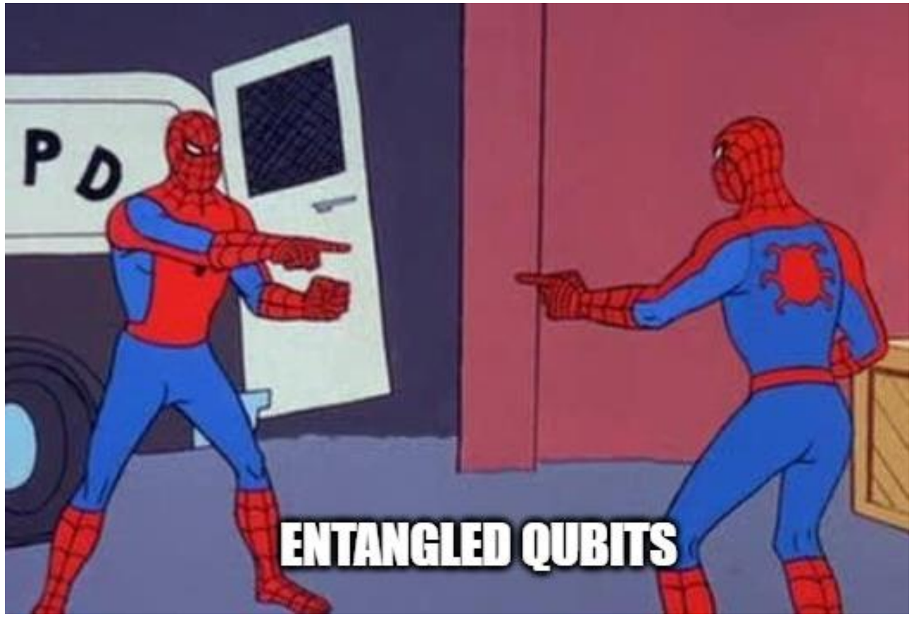
Postulates of Quantum Computing (2)

Quantum Entangled

Example: Bell's states

$$\frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right) \qquad \frac{1}{\sqrt{2}}\left(|01\rangle + |10\rangle\right)$$

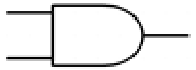
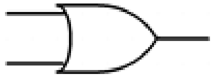
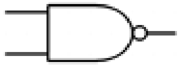
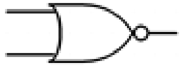
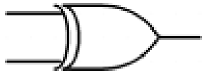
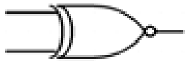
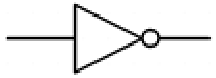
$$\frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right) \qquad \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$



3. State Change

Postulates of Quantum Computing (3)

Classically: logic gates

Logic Gate	Symbol	Description	Boolean
AND		Output is at logic 1 when, and only when all its inputs are at logic 1,otherwise the output is at logic 0.	$X = A \cdot B$
OR		Output is at logic 1 when one or more are at logic 1.If all inputs are at logic 0,output is at logic 0.	$X = A+B$
NAND		Output is at logic 0 when,and only when all its inputs are at logic 1,otherwise the output is at logic 1	$X = \overline{A \cdot B}$
NOR		Output is at logic 0 when one or more of its inputs are at logic 1.If all the inputs are at logic 0,the output is at logic 1.	$X = \overline{A+B}$
XOR		Output is at logic 1 when one and Only one of its inputs is at logic 1. Otherwise is it logic 0.	$X = A \oplus B$
XNOR		Output is at logic 0 when one and only one of its inputs is at logic1.Otherwise it is logic 1. Similar to XOR but inverted.	$X = \overline{A \oplus B}$
NOT		Output is at logic 0 when its only input is at logic 1, and at logic 1 when its only input is at logic 0.That's why it is called and INVERTER	$X = \overline{A}$

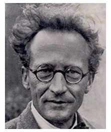
Quantumly

The state change of a closed quantum system is described by a unitary operator

$$i \frac{d|\psi\rangle}{dt} = H|\psi\rangle \quad \Rightarrow \quad |\psi(t)\rangle = e^{-iHt}|\psi(0)\rangle$$

$$U = e^{-iHt}$$

Schrodinger Equation

$\{\psi =$  $\}$

Quantumly: Quantum Gates

X Gate
Bit–flip, Not

$$X \equiv \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \beta|0\rangle + \alpha|1\rangle$$

Z Gate
Phase–flip

$$Z \equiv \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \alpha|0\rangle - \beta|1\rangle$$

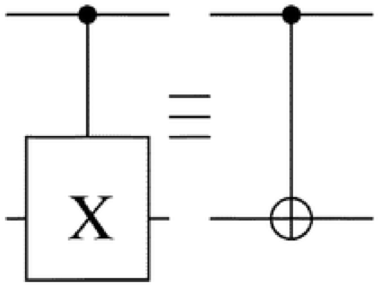
H Gate
Hadamard

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

T Gate

$$T \equiv \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \alpha|0\rangle + e^{i\pi/4}\beta|1\rangle$$

Controlled Not
Controlled X
CNot



$$\equiv \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = a|00\rangle + b|01\rangle + d|10\rangle + c|11\rangle$$

Postulates of Quantum Computing (4)

4. Measurement

Classically

Measuring returns the state of a bit with certainty

$|0\rangle \xrightarrow{\text{Measure}}$ Outcome $|0\rangle$

$|1\rangle \xrightarrow{\text{Measure}}$ Outcome $|1\rangle$

Measurements do not affect the state of a bit

Quantumly

Measuring returns the bit state with some probability

Outcome

Measure

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

$|0\rangle$ *with* $P_r = |\alpha|^2$

$|1\rangle$ *with* $P_r = |\beta|^2$

Measurement affects the state of a qubit

Postulates of Quantum Computing (4)

Quantumly

- To **any observable** physical quantity is associated an **hermitian operator** *O*

$$O|o_i\rangle = o_i|o_i\rangle$$

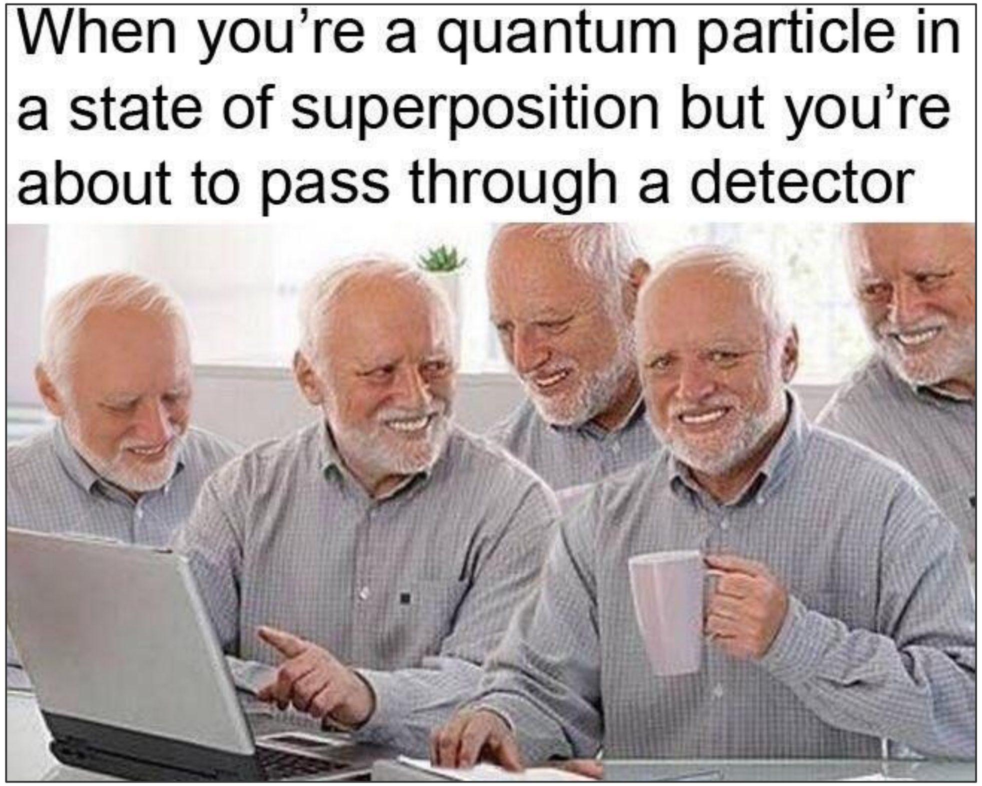
- A **measurement** outcomes are the **possibile eigenvalues** $\{o_i\}$.

- The **probability of obtaining** o_i as a result of the measurement is

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

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

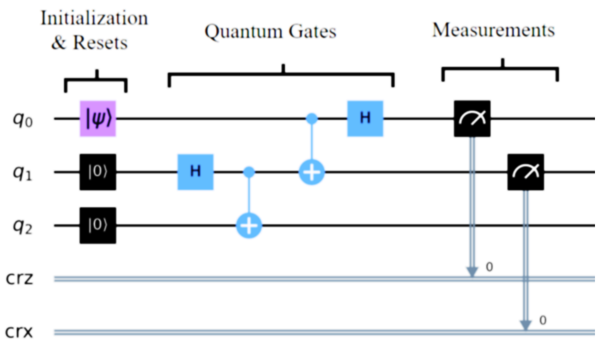
$$|\psi\rangle \rightarrow |o_i\rangle$$



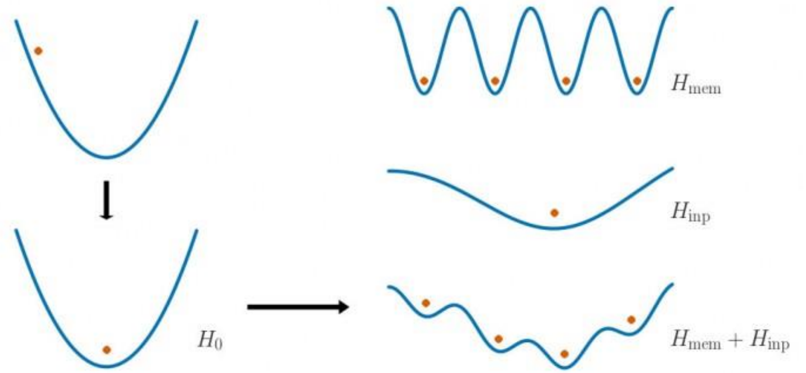
Quantum Computing Models

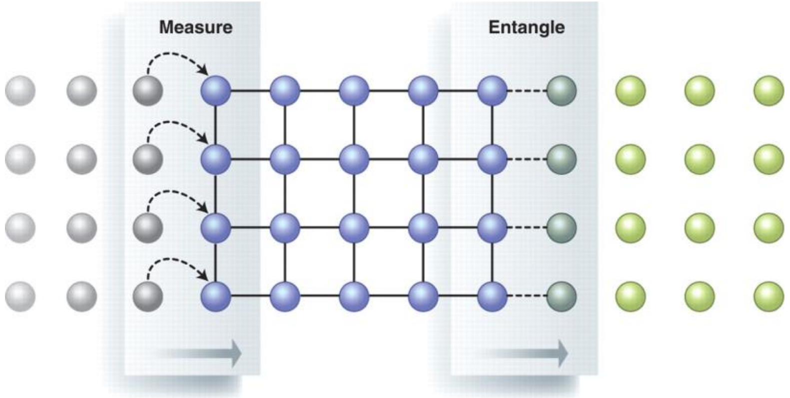
Quantum Computing Models

Gate Model Quantum Computation

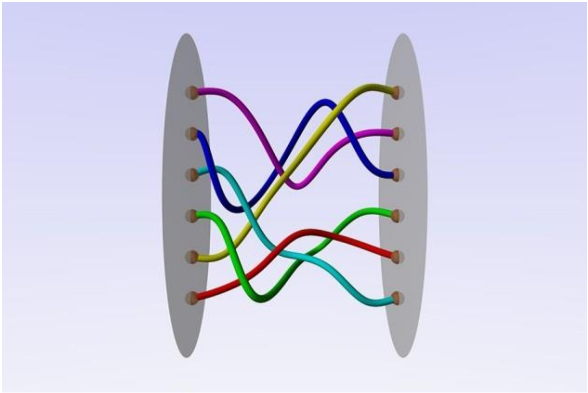


Adiabatic Quantum Computation





Measurement Based Quantum Computation



Topological Quantum Computation

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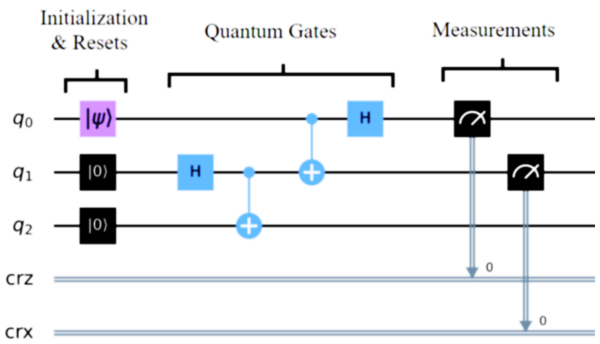
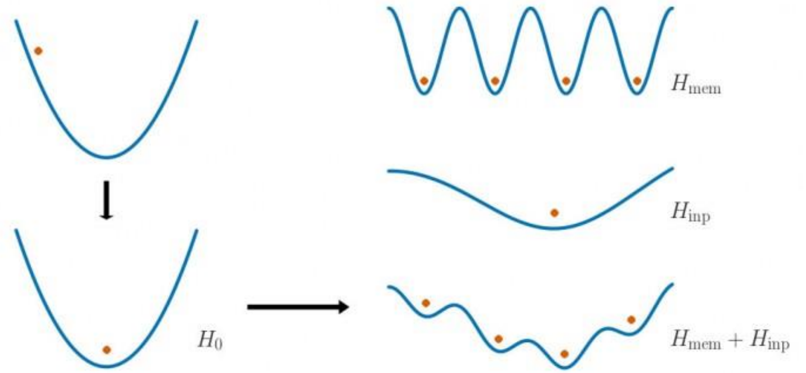
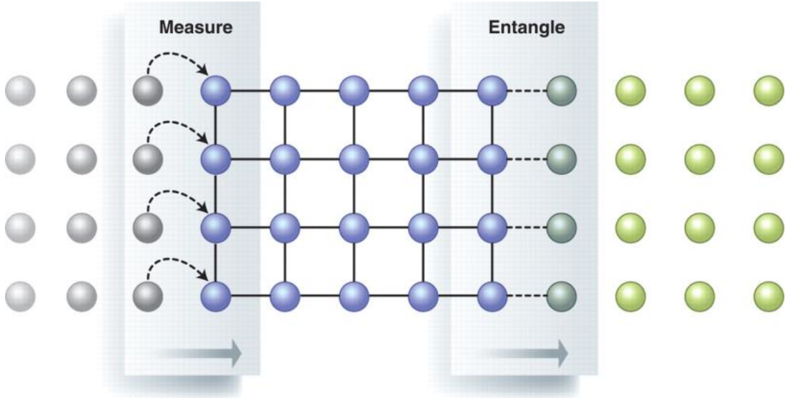
Quantum Computing Models

Gate Model Quantum Computation

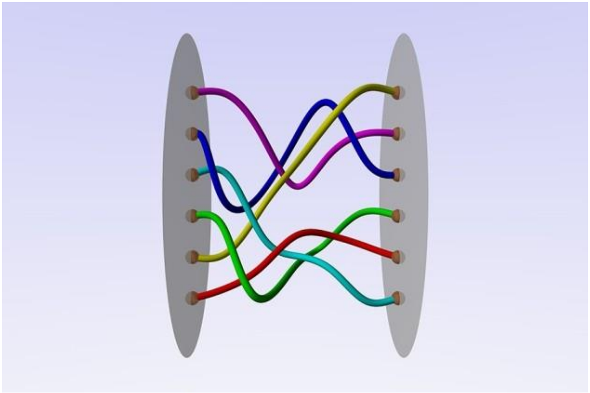


Adiabatic Quantum Computation





Measurement Based Quantum Computation



Topological Quantum Computation

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Quantum Circuits

Quantum Algorithm = Quantum Circuit

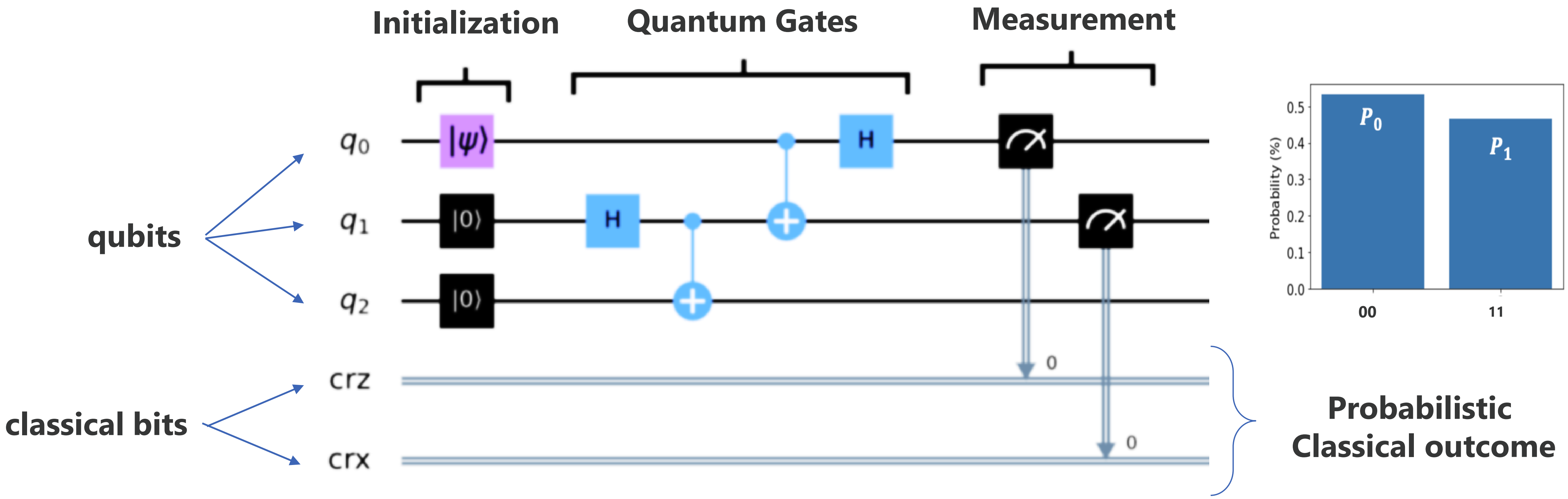
A quantum circuit with *n* input qubits and *n* output qubits is defined by a unitary transformation

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

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

$$U^{-1} = U^\dagger$$

Quantum Circuits



It is necessary to run the circuit and measure multiple times to reconstruct the probability distribution

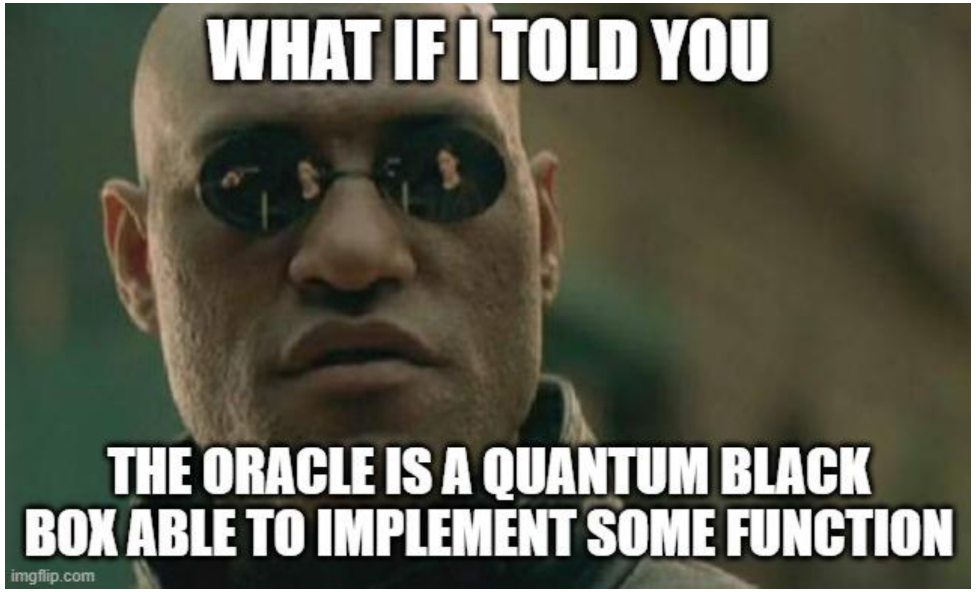
Quantum Parallelism

Oracle: Function evaluation

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

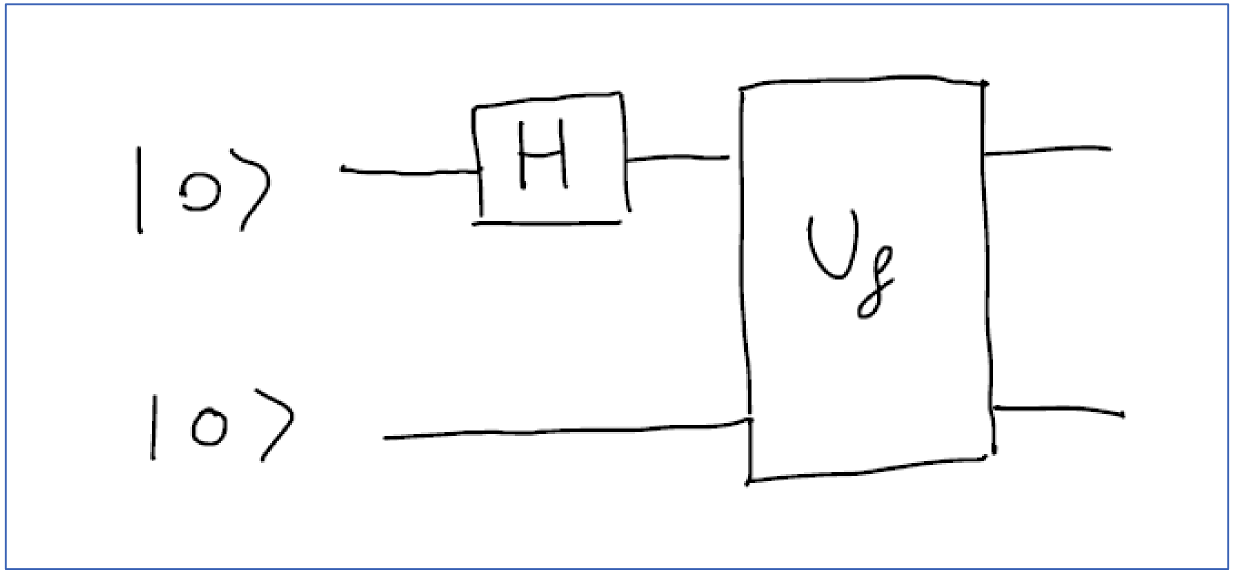
$$|x\rangle|y\rangle \xrightarrow{U_f} |x\rangle|y \oplus f(x)\rangle$$

where $x \in \{0,1\}^N$ $y \in \{0,1\}^M$

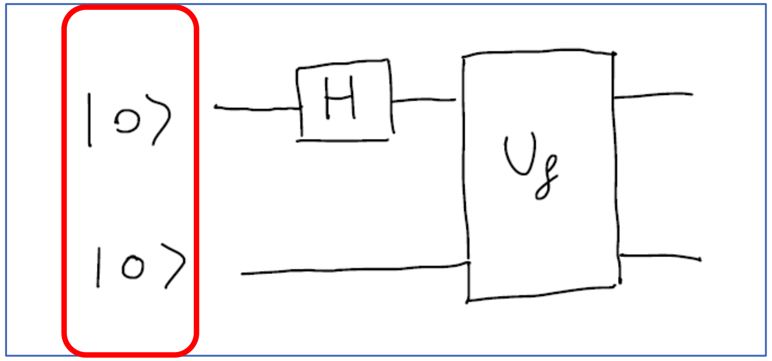


Quantum Parallelism

Consider the following quantum circuit



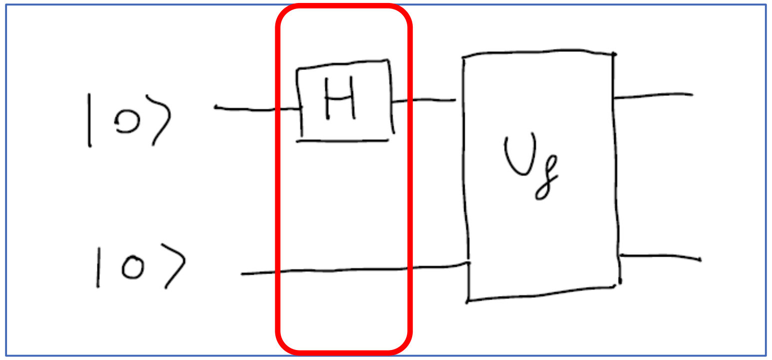
Quantum Parallelism



Quantum Parallelism: step-by-step

$$|0\rangle|0\rangle$$

Quantum Parallelism



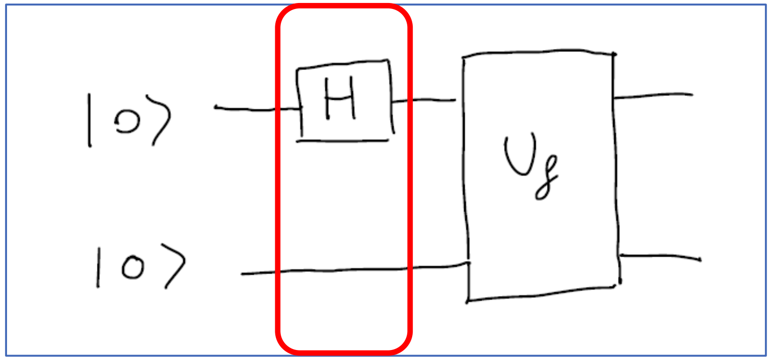
Quantum Parallelism: step-by-step

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

Hadamard Gate

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

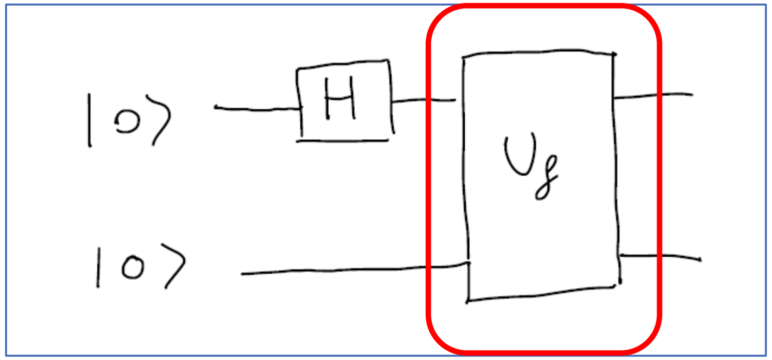
$$H|1\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle - |1\rangle\right)$$



Quantum Parallelism: step-by-step

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

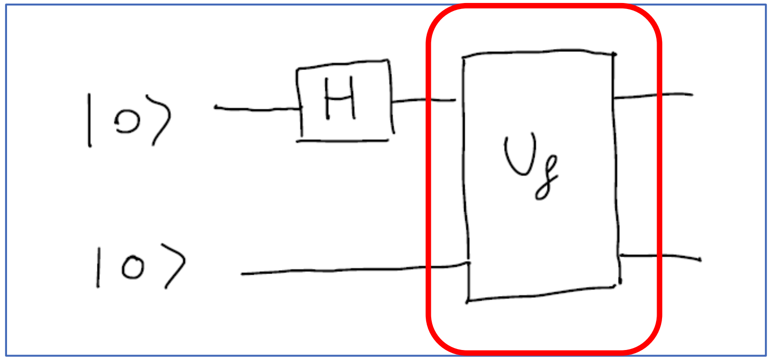
Quantum Parallelism



Quantum Parallelism: step-by-step

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

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



Quantum Parallelism: step-by-step

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

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

Quantum Parallelism

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

This is a remarkable state!

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

Quantum Parallelism

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

This is a remarkable state!

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

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

Quantum algorithms exploit quantum parallelism to solve <u>some</u> problems faster than classical algorithms

Quantum Algorithms

Facorization Problem

Given N , find the two prime numbers such that

$$N = p \times q$$

Facorization Problem

Given N , find the two prime numbers such that

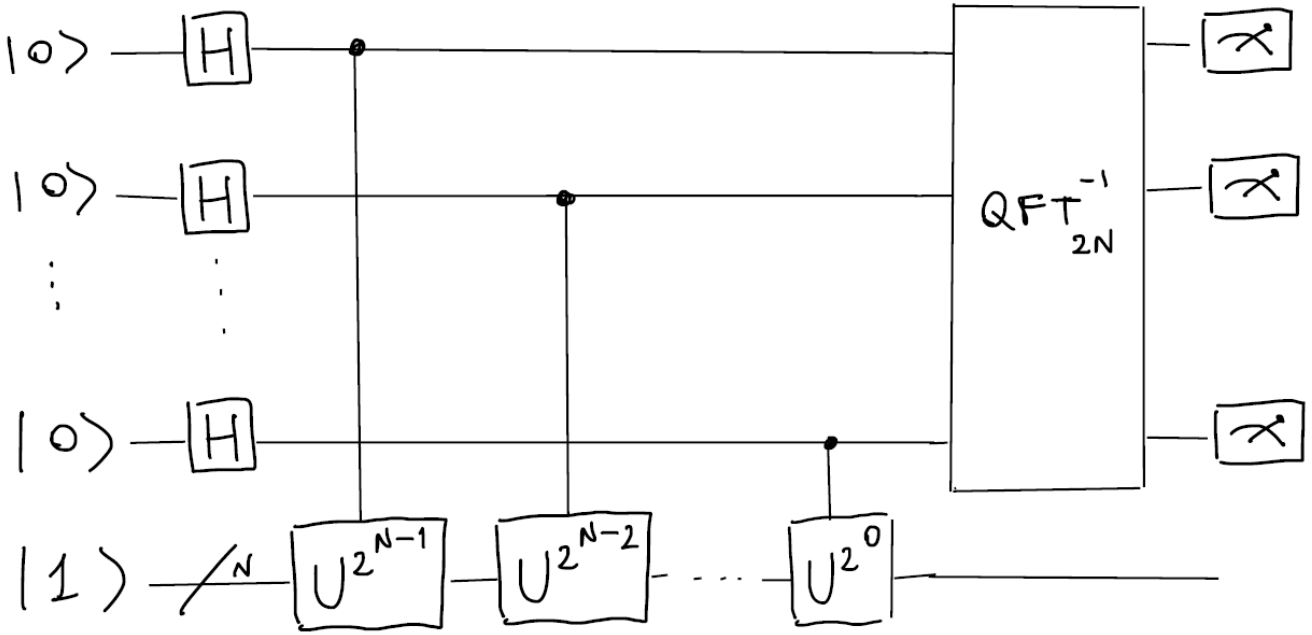
$$N = p \times q$$

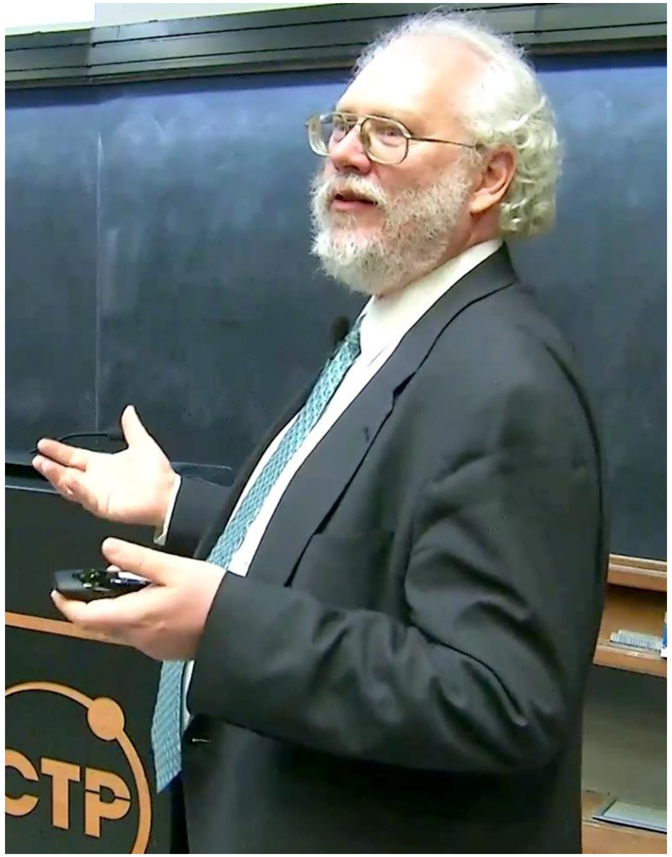
Classically: Finding solution requires **exponential time**

→ Used in the RSA crypto system

Shor Algorithm

Quantum Algorithm to solve factorization in polynomial time



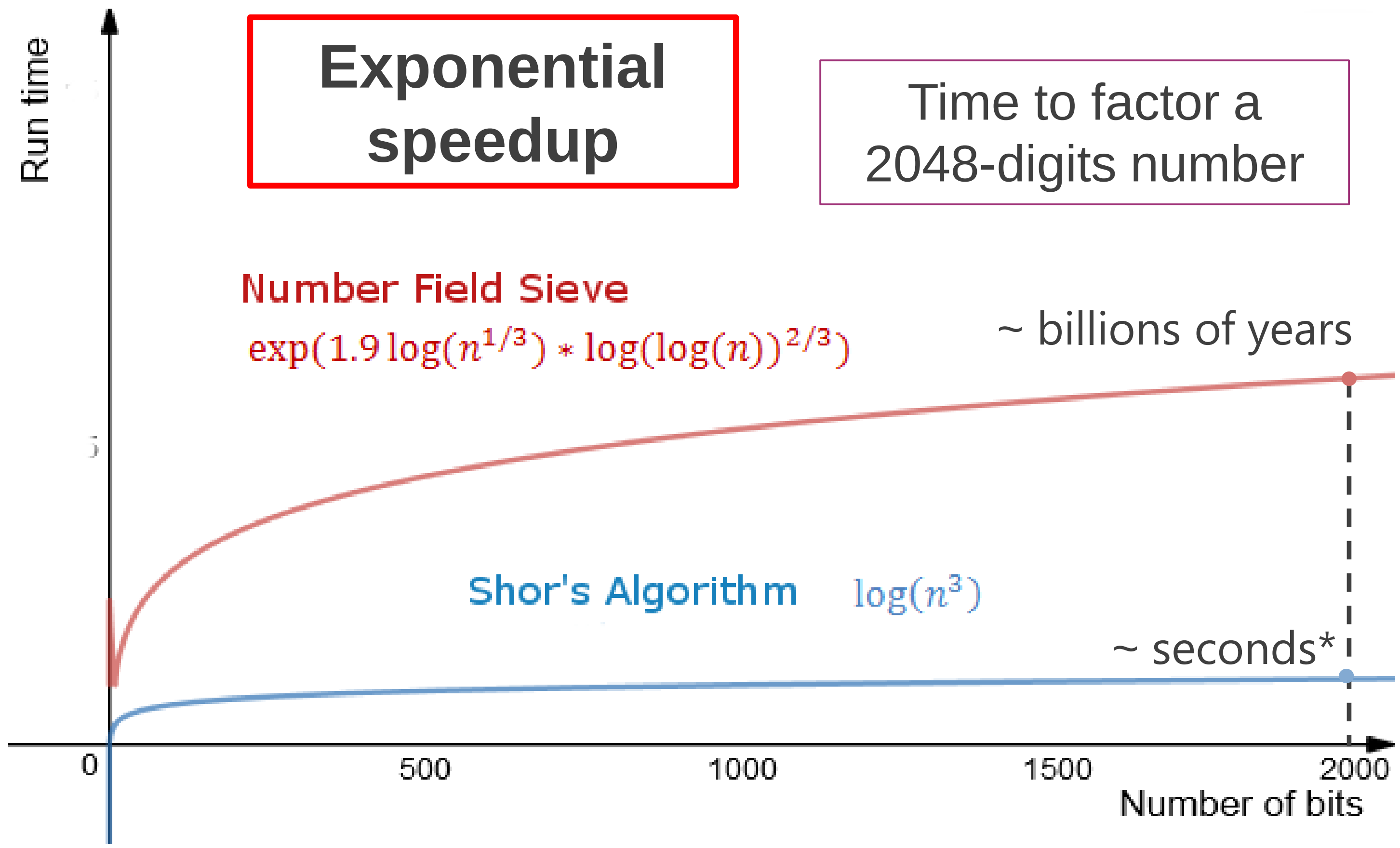


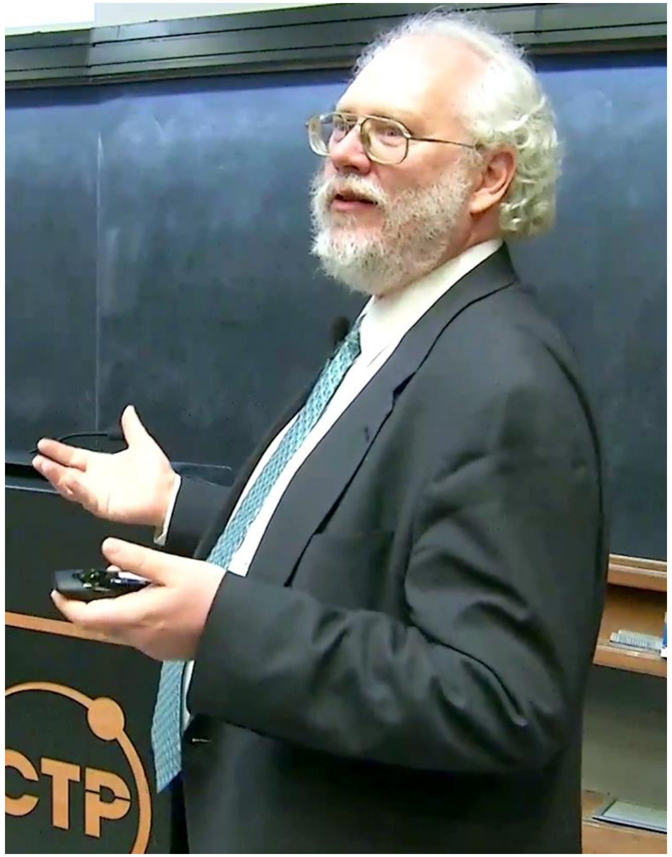
https://www.youtube.com/watch?v=6qD9XElTpCE

Shor Algorithm

Exponential speedup

Time to factor a 2048-digits number

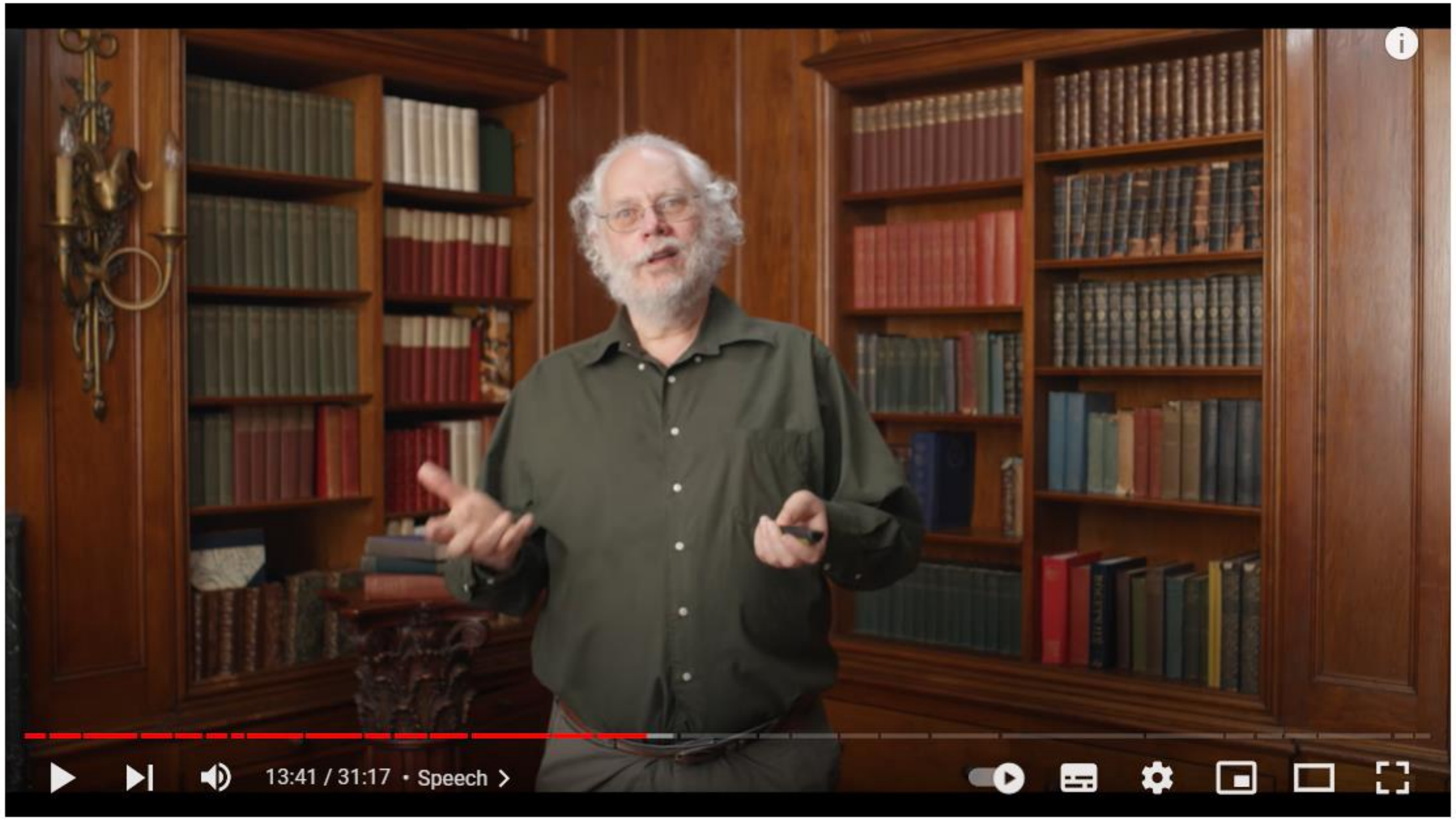




* Assuming we have a fault-tolerant quantum computer capable of executing Shor’s algorithm by applying gates at the speed of current quantum computers based on superconducting circuits

Shor Algorithm

https://www.youtube.com/watch?v=6qD9XElTpCE



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

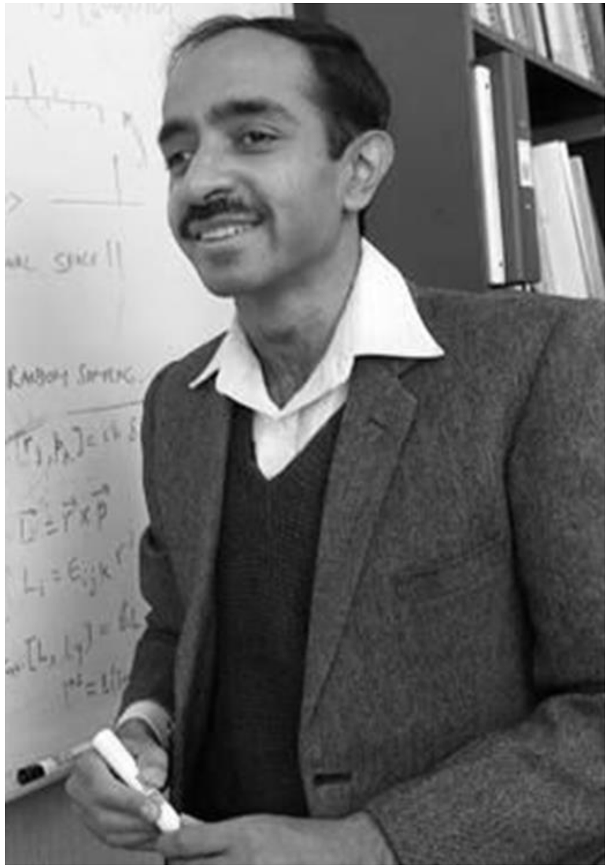
Grover search algorithm

Run-time brute-force algorithm:

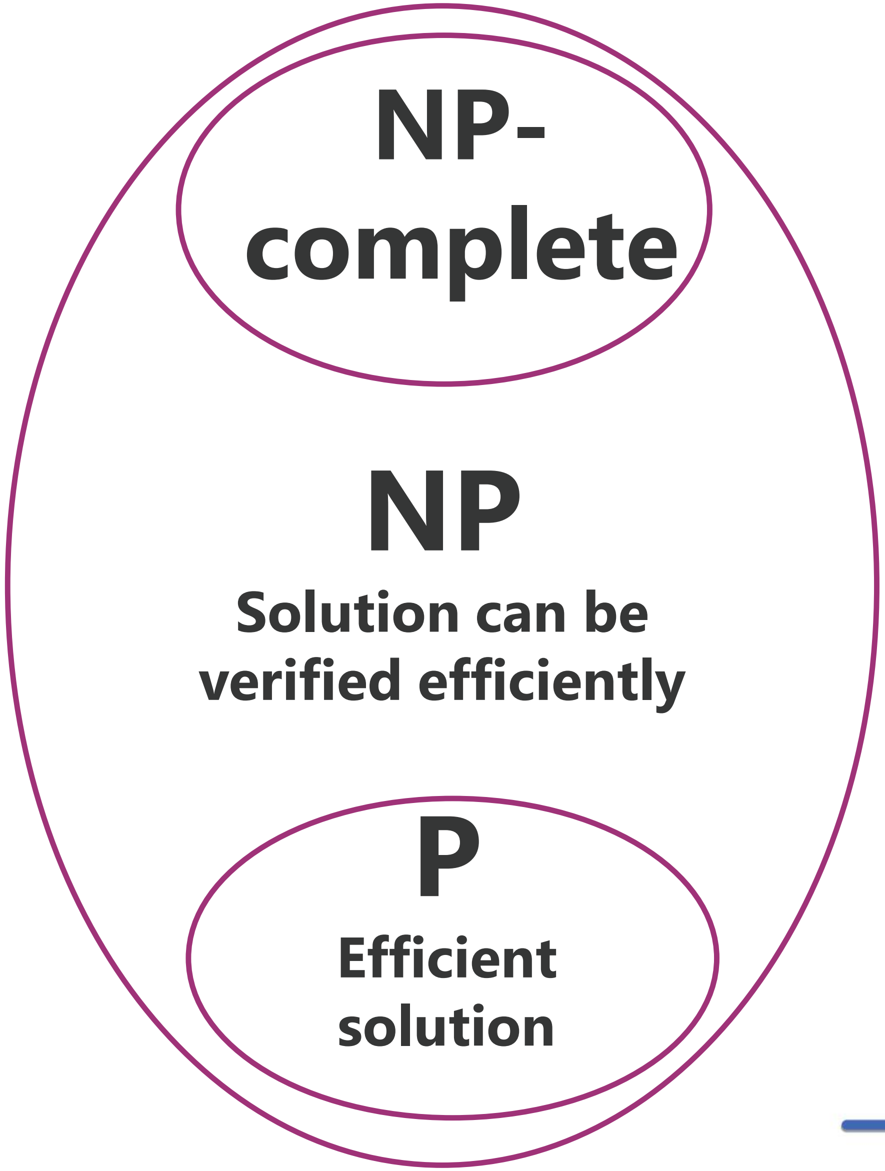
$$d^N$$

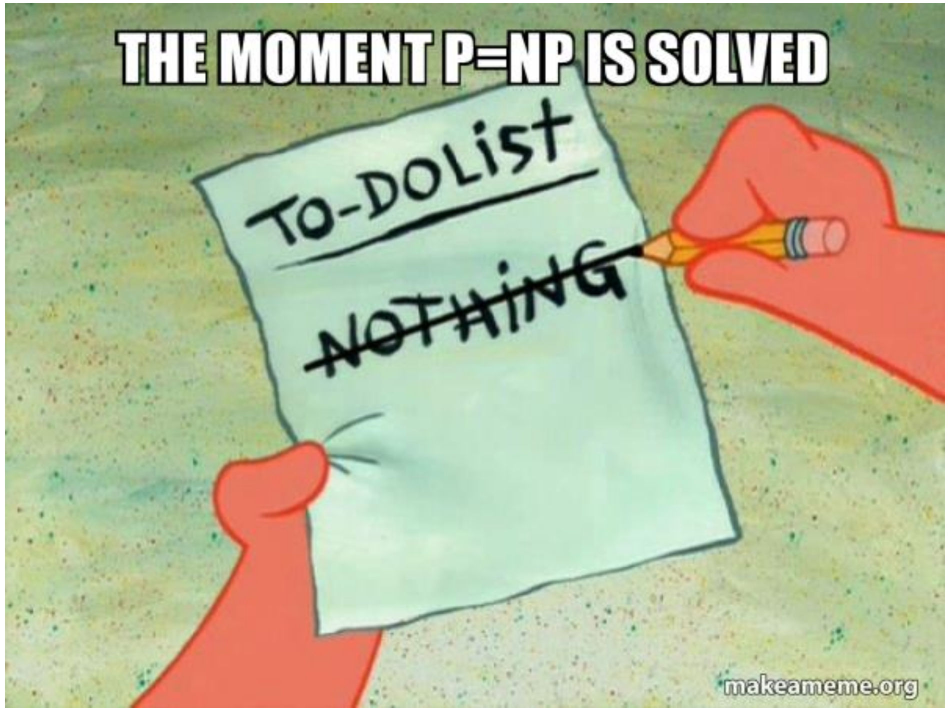
Run-time Grover search:

$$\sqrt{d^N}$$

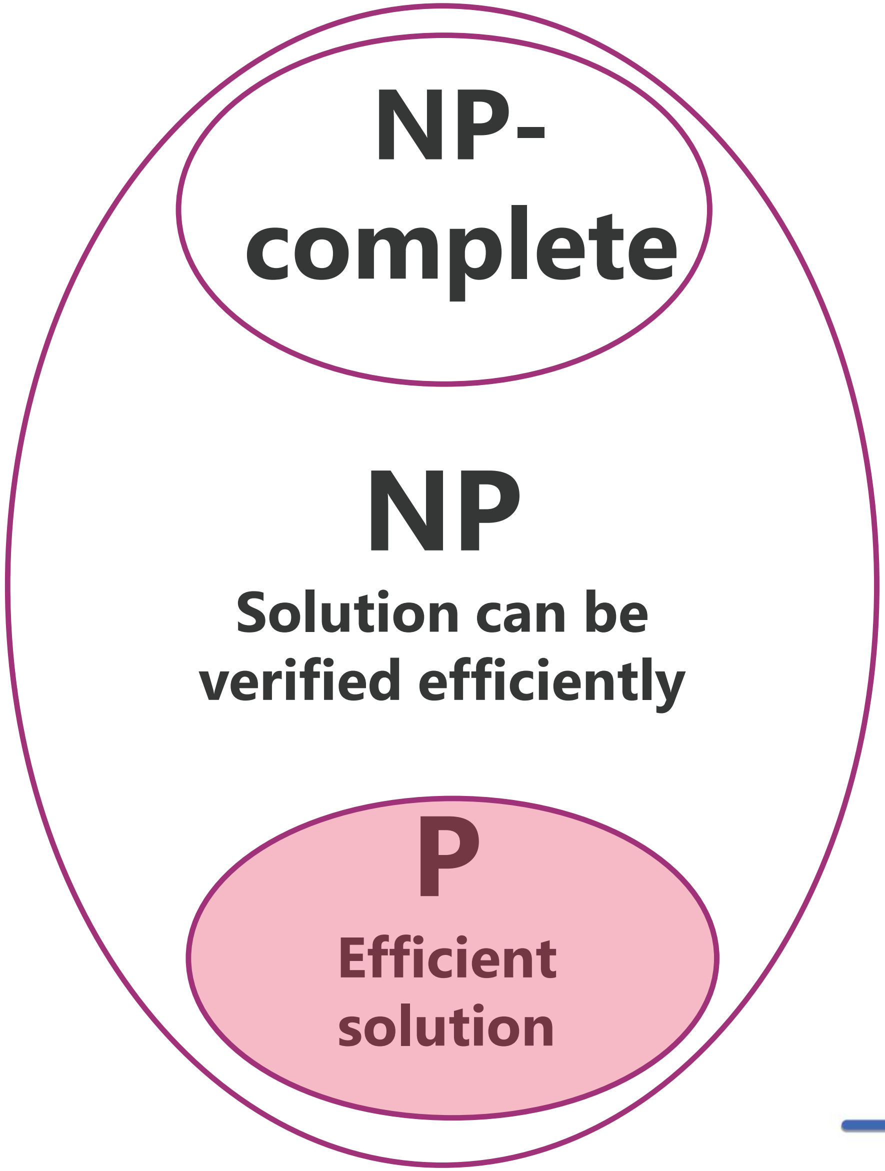


Complexity classes

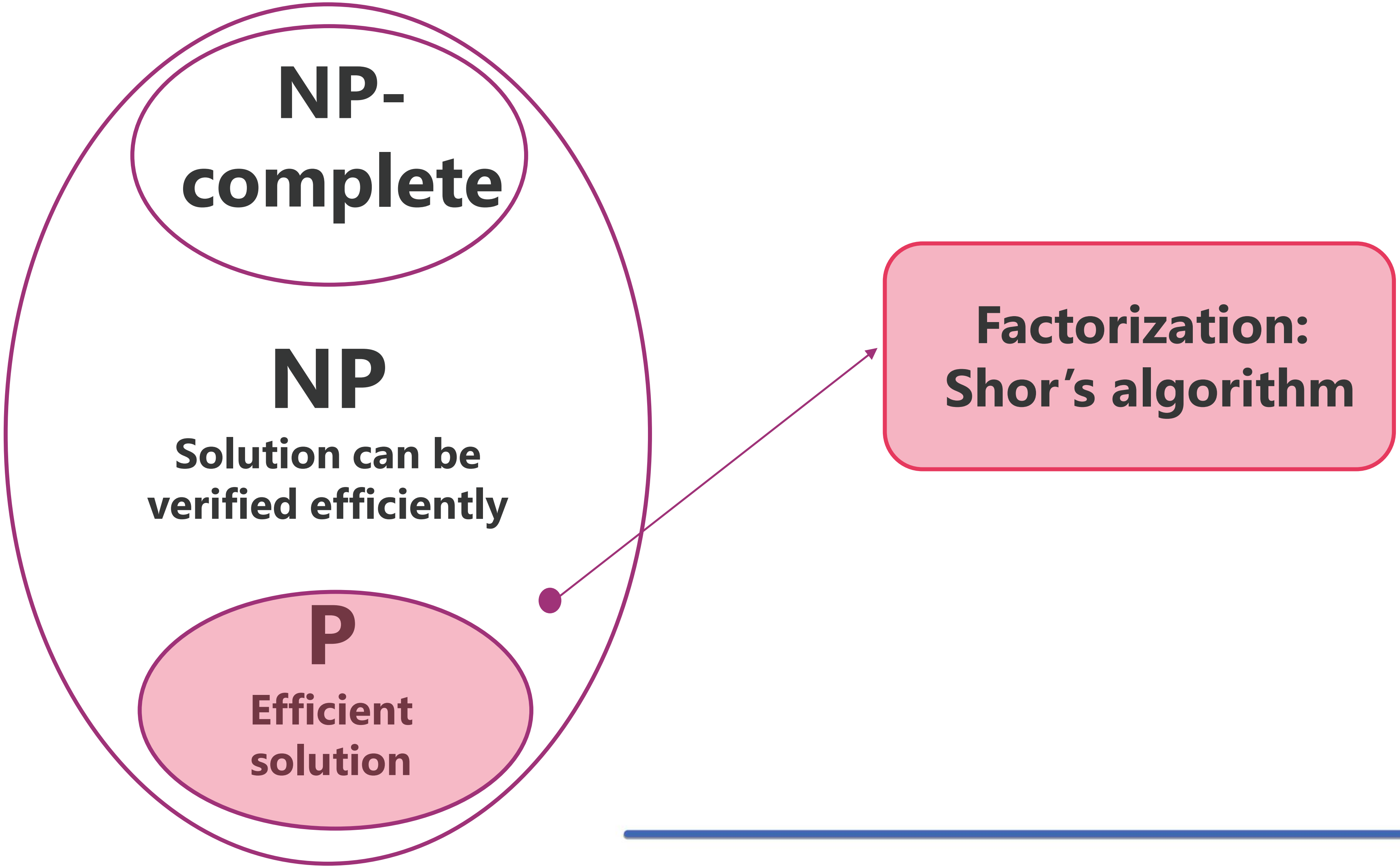




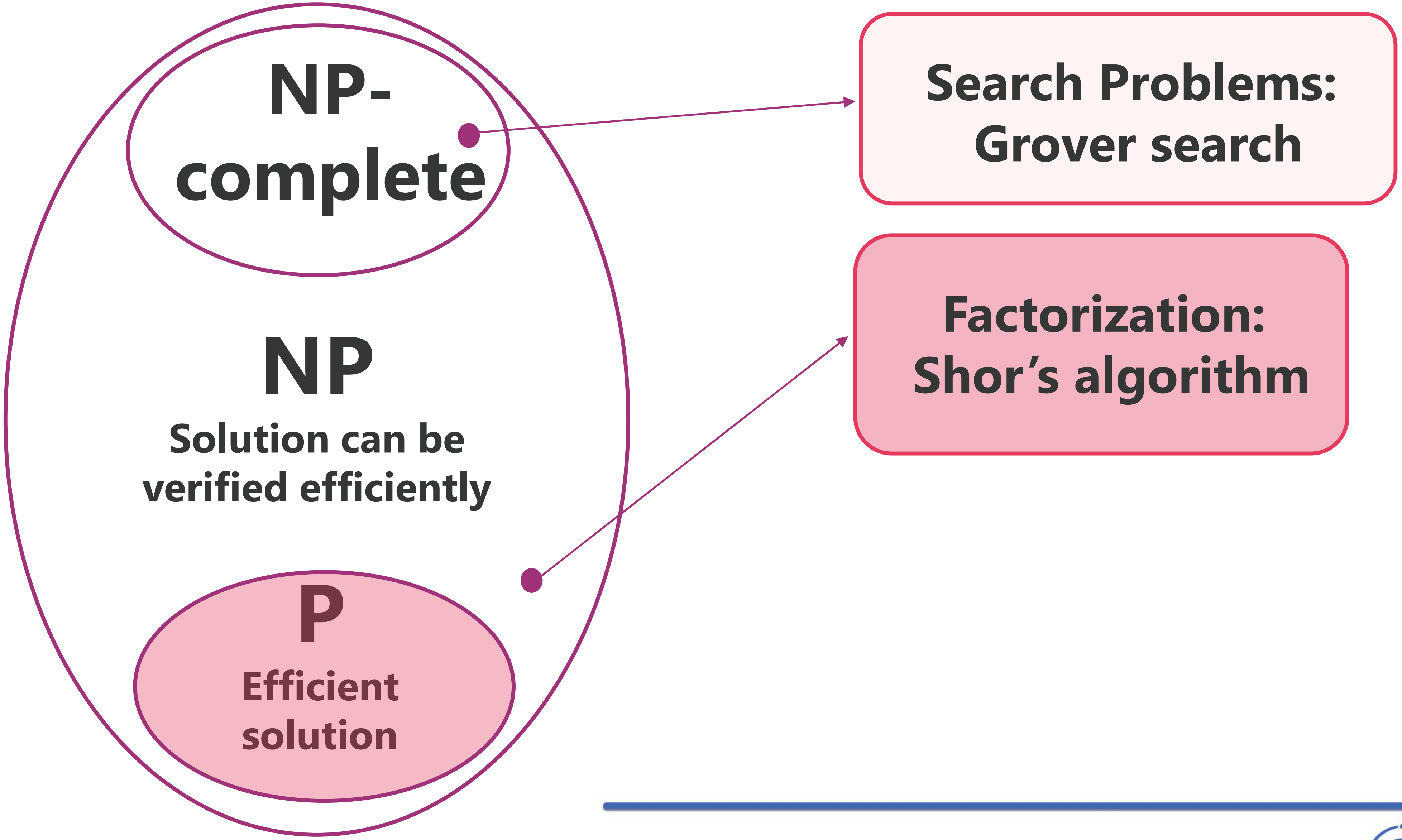
Complexity classes



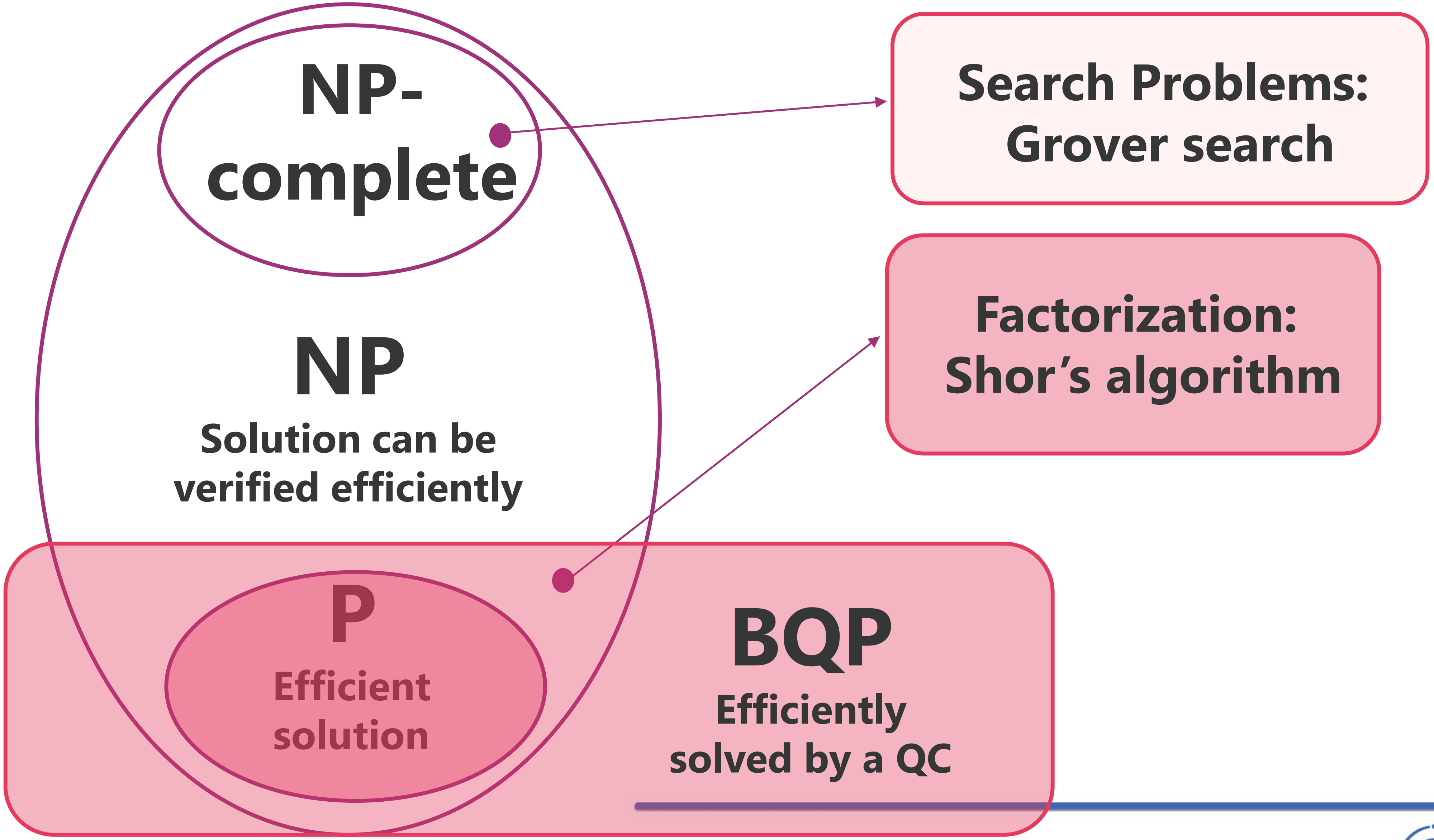
Complexity classes



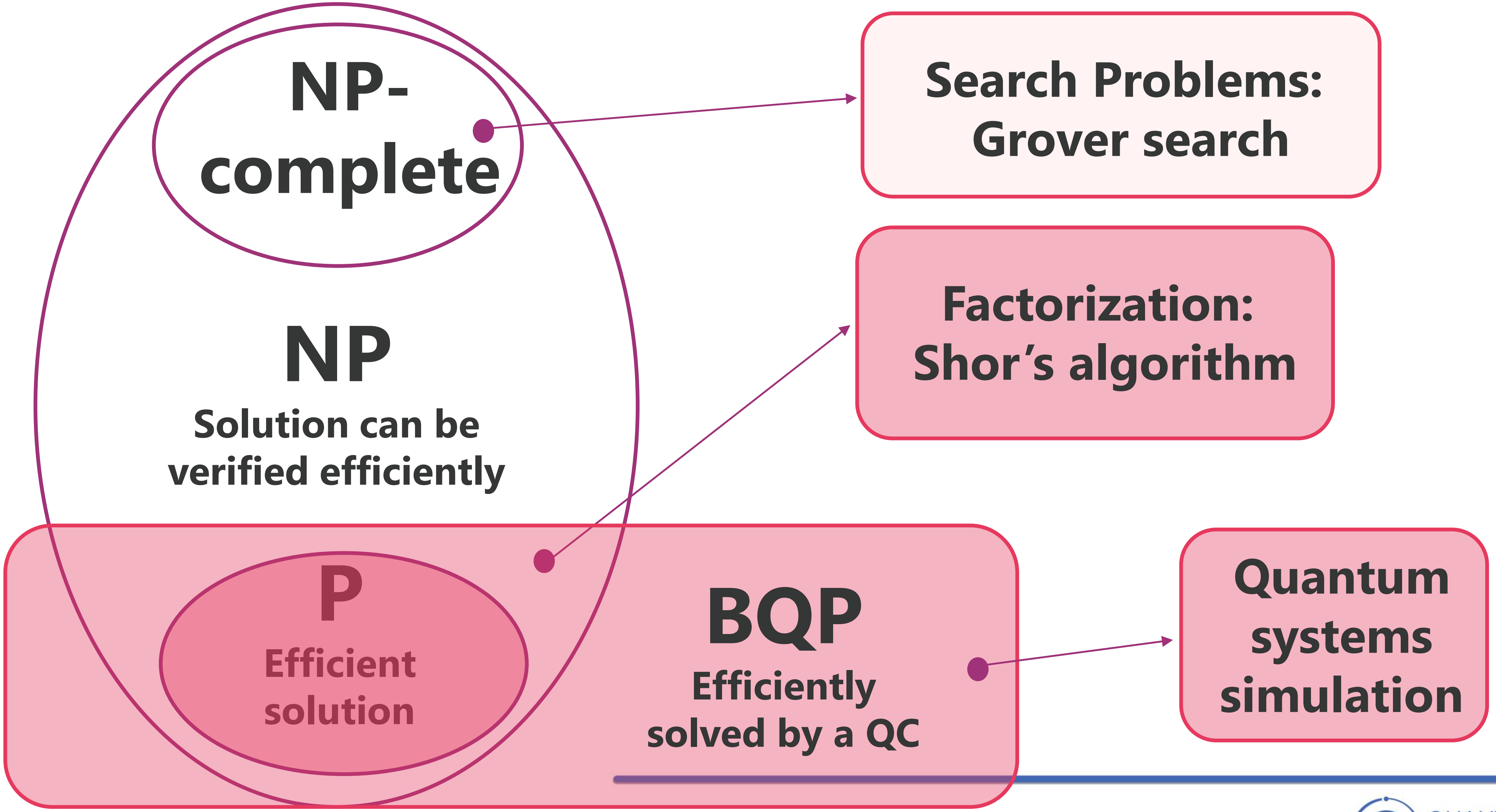
Complexity classes



Complexity classes



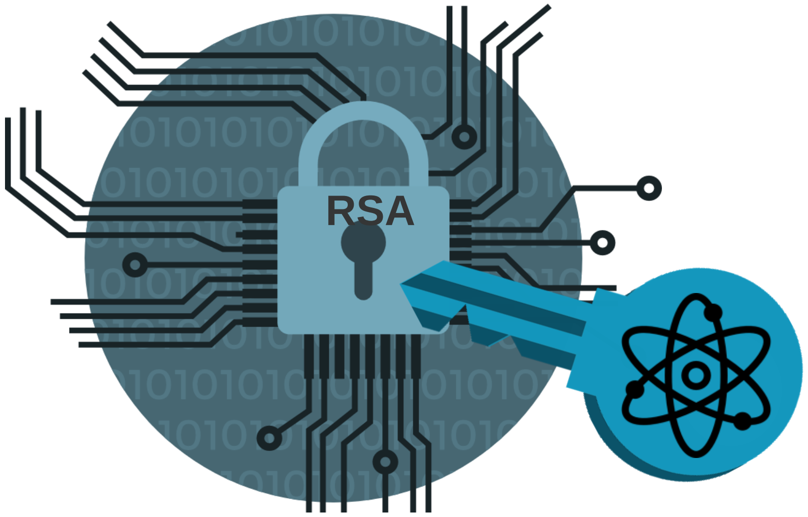
Complexity classes



Old School Quantum Algorithms

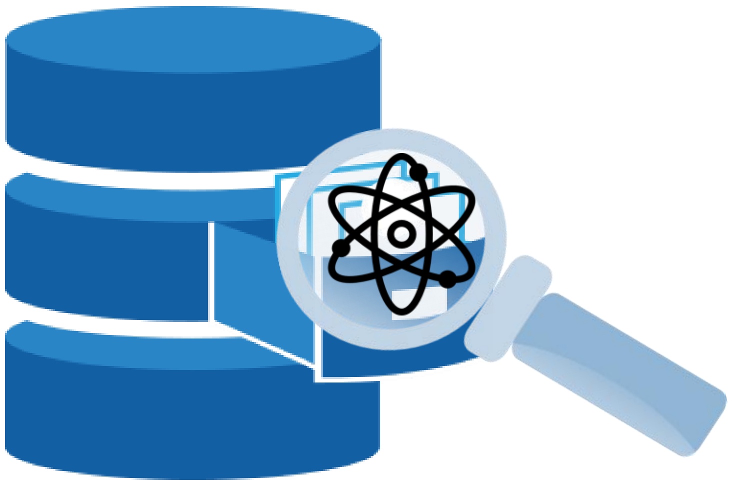
Cryptography

Shor’s Algorithm
Exponential Speedup



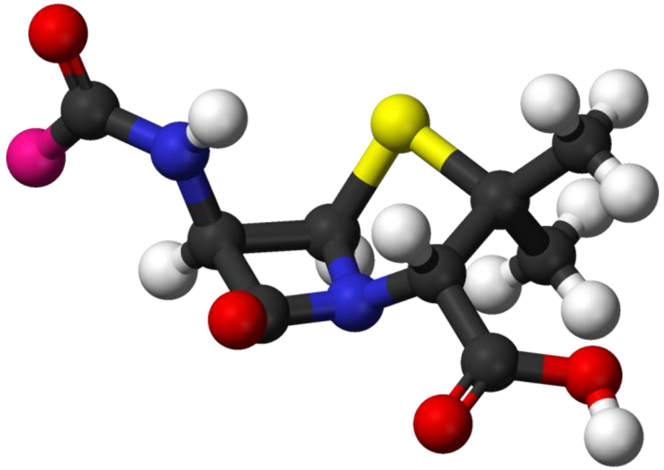
Optimization

Grover’s Algorithm
Quadratic Speedup



Chemistry

Quantum Simualtion
Exponential Speedup



Quantum Algorithm Zoo:
https://quantumalgorithmzoo.org/

Old School Quantum Algorithms

Cryptography

Shor's Algorithm
Exponential Speedup

Optimization

Grover's Algorithm
Quadratic Speedup

Chemistry

Quantum Simualtion
Exponential Speedup

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

Common sources of errors in QC

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

QEC: introductiory guide
https://arxiv.org/abs/1907.11157

Old School Quantum Algorithms: Error correction

Cryptography

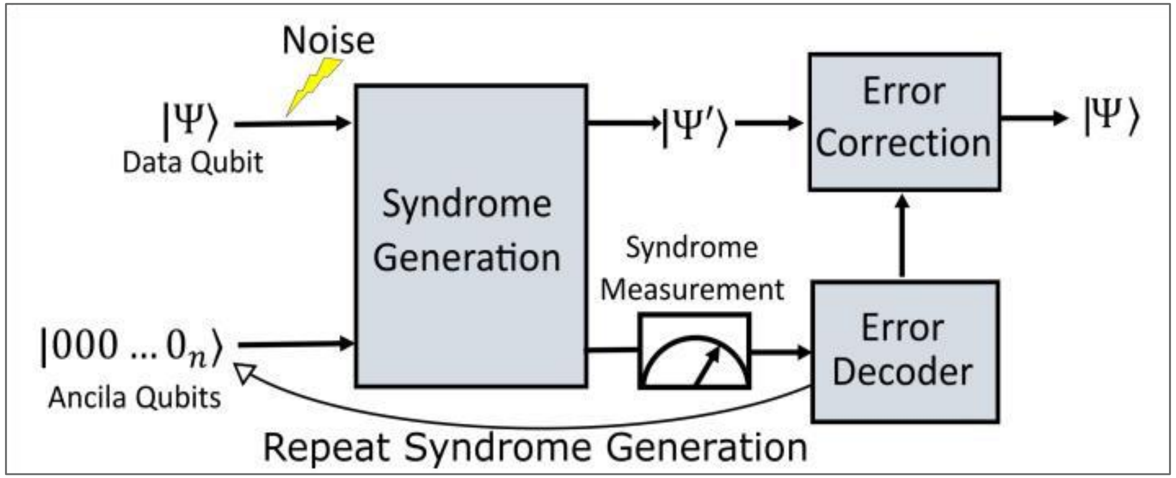
Shor's Algorithm
Exponential Speedup

Optimization

Grover's Algorithm
Quadratic Speedup

Chemistry

Quantum Simualtion
Exponential Speedup



QEC: introductiory guide
https://arxiv.org/abs/1907.11157

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

Old School Quantum Algorithms: Error correction

Cryptography

Shor's Algorithm
Exponential Speedup

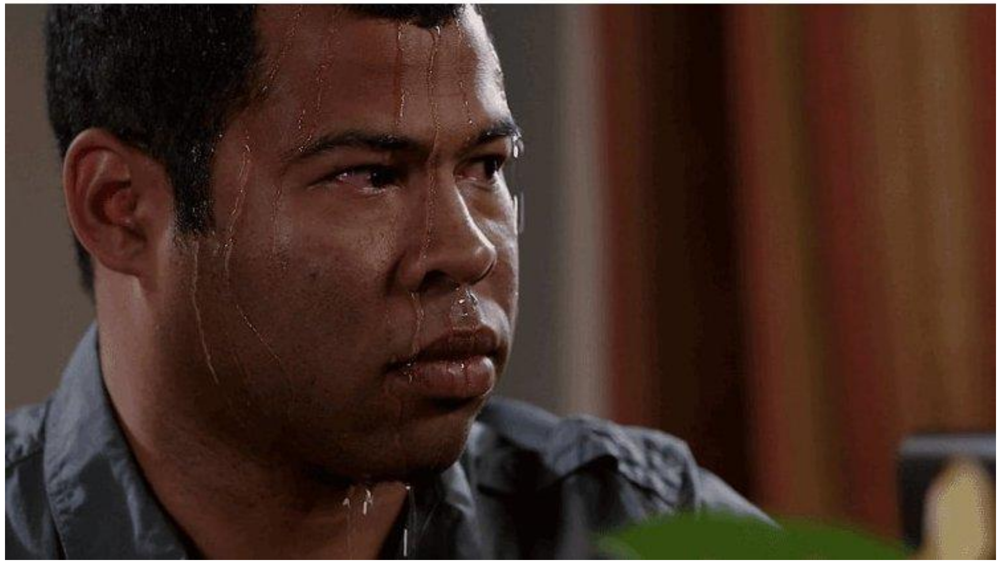
Optimization

Grover's Algorithm
Quadratic Speedup

Chemistry

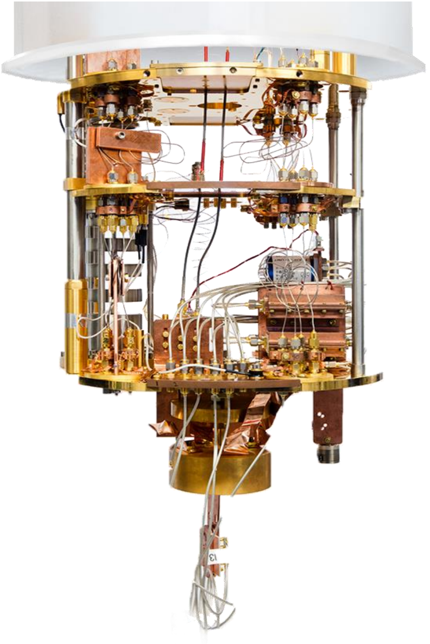
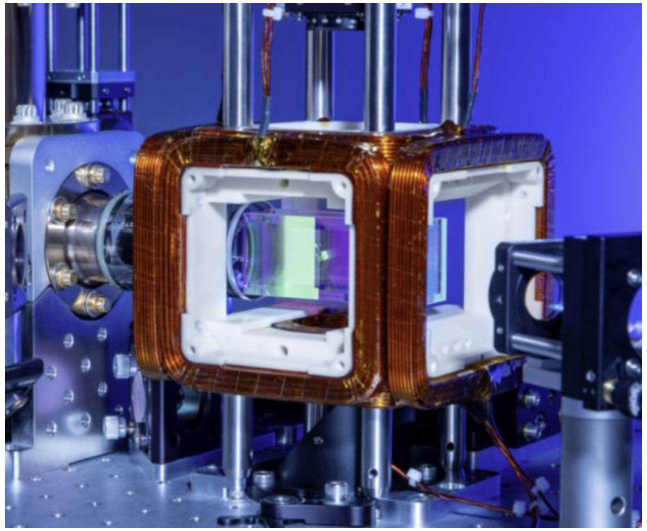
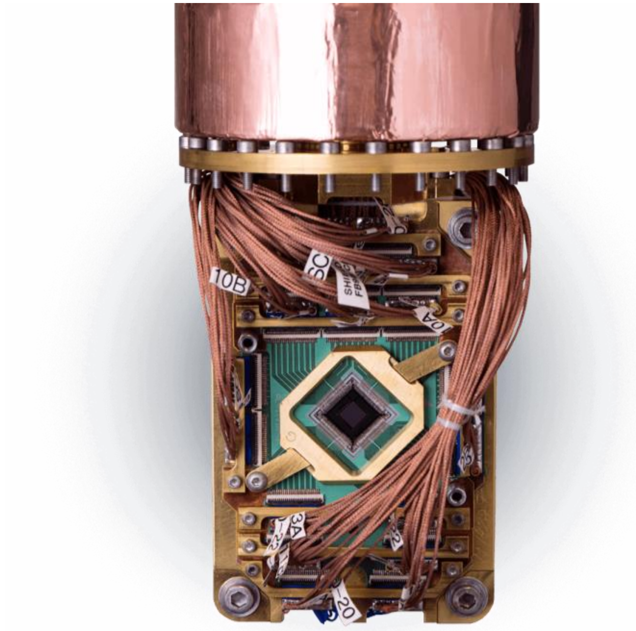
Quantum Simualtion
Exponential Speedup

When you see the ratio of physical to logical qubits for fault tolerant quantum computation



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

How can we use the small and imperfect Quantum Devices (NISQ) we have today?

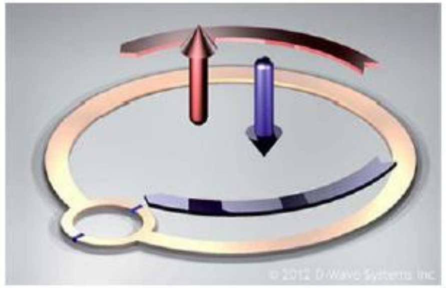
The NISQ Era

The NISQ Era

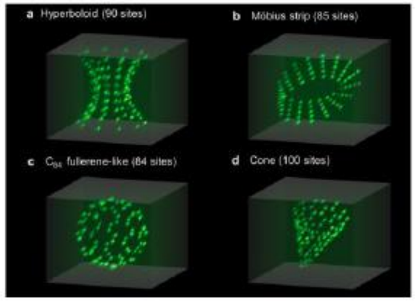
NISQ = Noisy Intermediate-Scale Quantum

Intermediate-Scale Quantum computers with no error correction

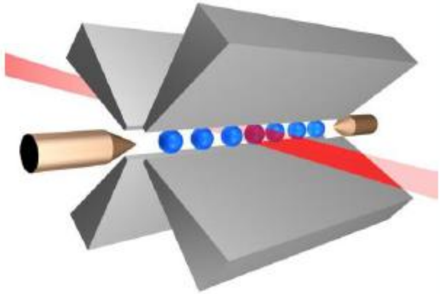
Different Qubit technologies



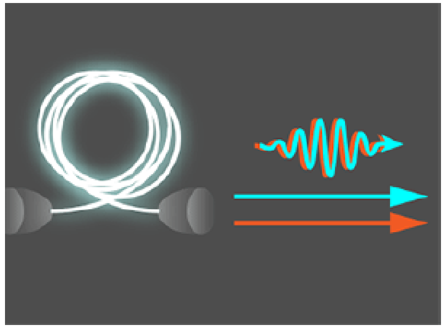
Superconducting



Neutral Atoms

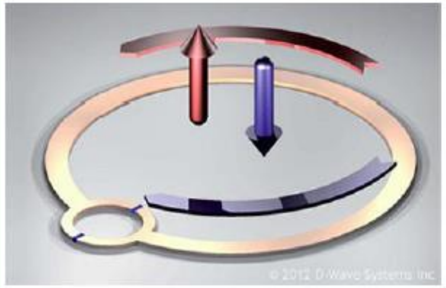


Trapped-Ions

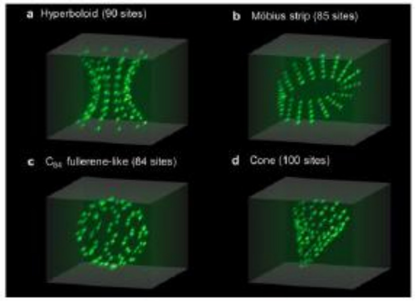


Photonic

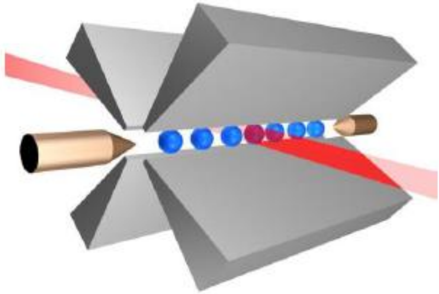
The NISQ Era



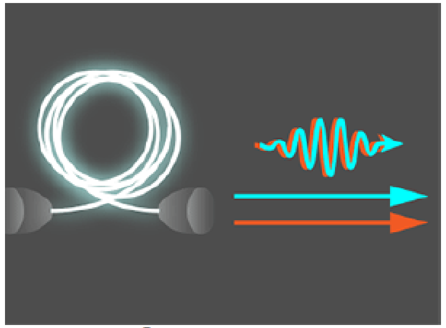
Superconducting



Neutral Atoms



Trapped-Ions



Photonic

Differences:

Topology: how qubits are connected togerther

Coherence Time (seconds): quantum superposition lifetime

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

Gate Fidelity (%) : Fidelity in gate operation

Qubit technologies

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

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

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

rigetti Google IBM Q QuTech OQC IQM Quantum Circuits, Inc 本源量子 Origin Quantum

https://quantumcomputingreport.com/

Qubit technologies

	Trapped Ions	Trapped Ions
Subtype	Hyperfine	Optical
Coherence Time (seconds)	3	0.2
Gate Fidelity (%)	99.92%	99.6%
Gate Delay (seconds)	2.00E-04	2.0E-04
Environment	Vacuum	Vacuum
Largest Device	32Q	20Q
Notable Players	IonQ Honeywell	AQT AQTION NextGenQ

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

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

IONQ
AQT
QUANTINUUM
oxford ionics
Universal Quantum

https://quantumcomputingreport.com/

Qubit technologies

	Photonics	Photonics
Subtype	Si_3N_4	Other
Coherence Time (seconds)		1.50E-04
Gate Fidelity (%)		
Gate Delay (seconds)		1.00E-09
Environment	Ambient, 2K only for Detectors	Ambient, 2K only for Detectors
Largest Device	216 continuos variable Qumode	20 photons
Notable Players	- Xanadu -QuiX	-PsiQ -Orca Computing

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

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

https://quantumcomputingreport.com/

Qubit technologies

	Neutral Atoms
Coherence Time (seconds)	3.20E-01
Gate Fidelity (%)	Expected to be around 98%
Gate Delay (seconds)	1.00E-06
Environment	Vacuum
Largest Device	200Q
Notable Players	-ColdQuanta -QuEra -Pasqal -Atom Computing

Pros: Long coherence times. Atoms are perfect and consistent. Strong connectivity, including more than 2Q. External cryogenics not required.
Cons: Requires ultra-high vacuums. Laser scaling challenging.

ColdQuanta

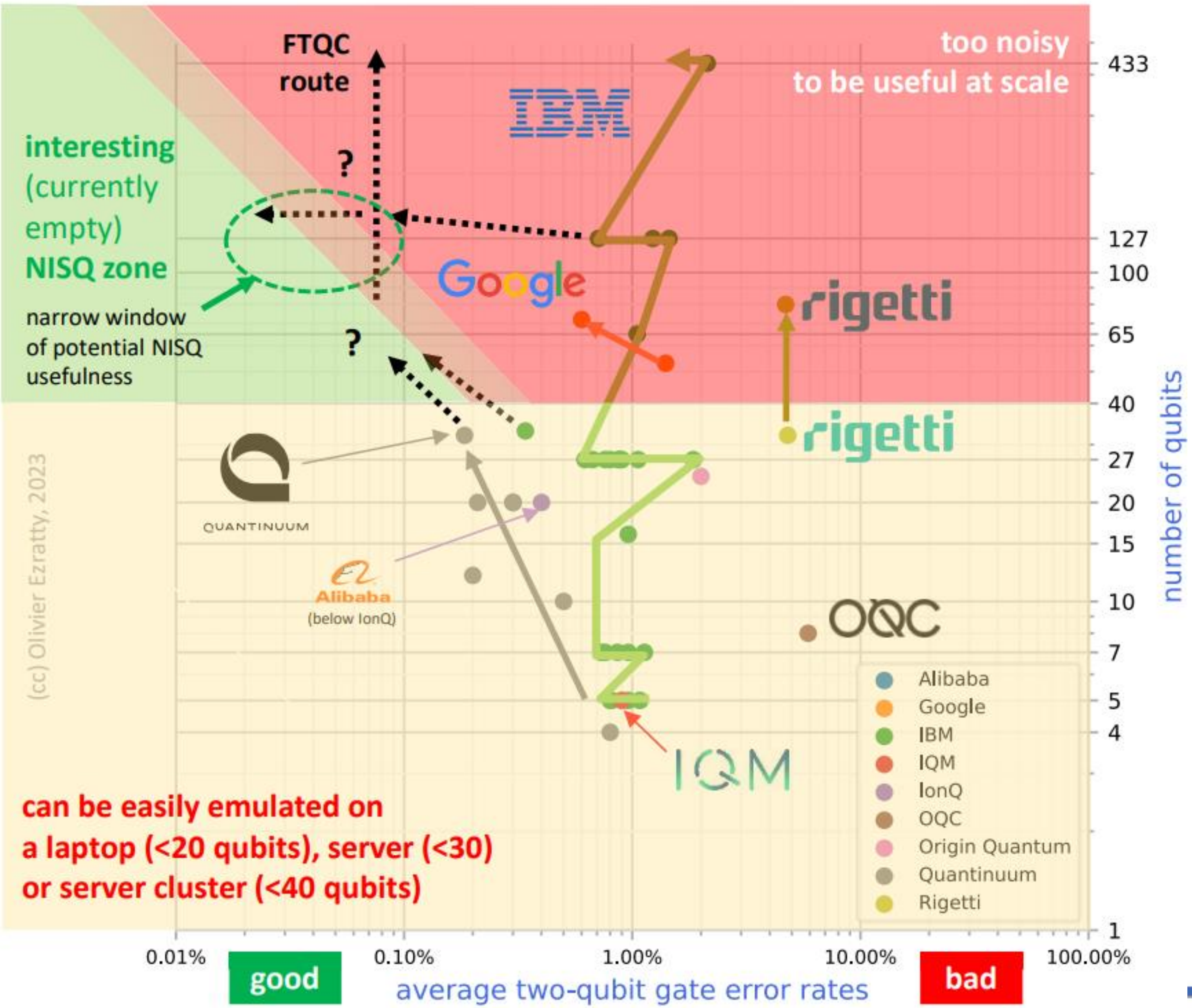
|QuEra⟩ COMPUTING INC.

atom computing

PASQAL

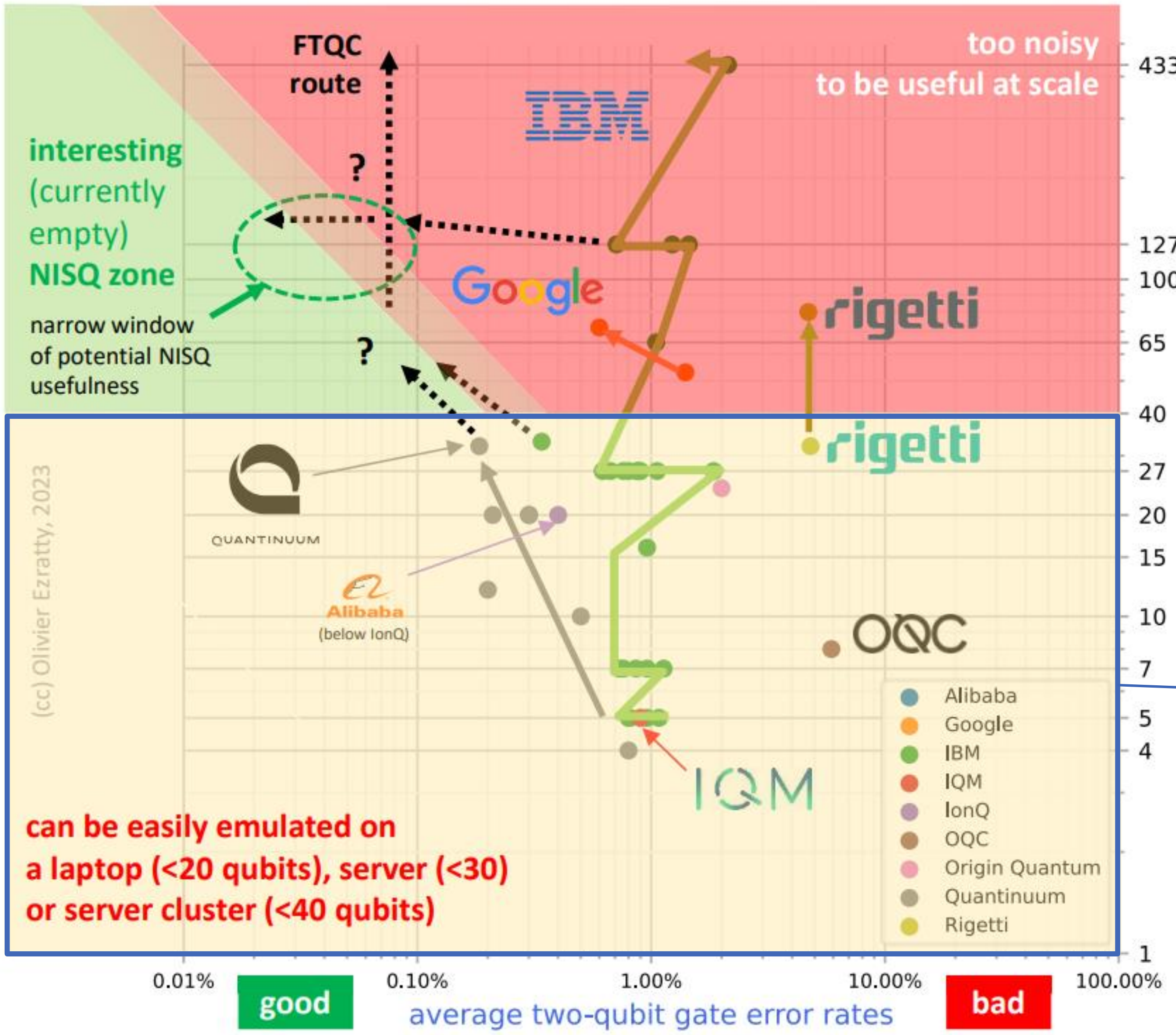
https://quantumcomputingreport.com/

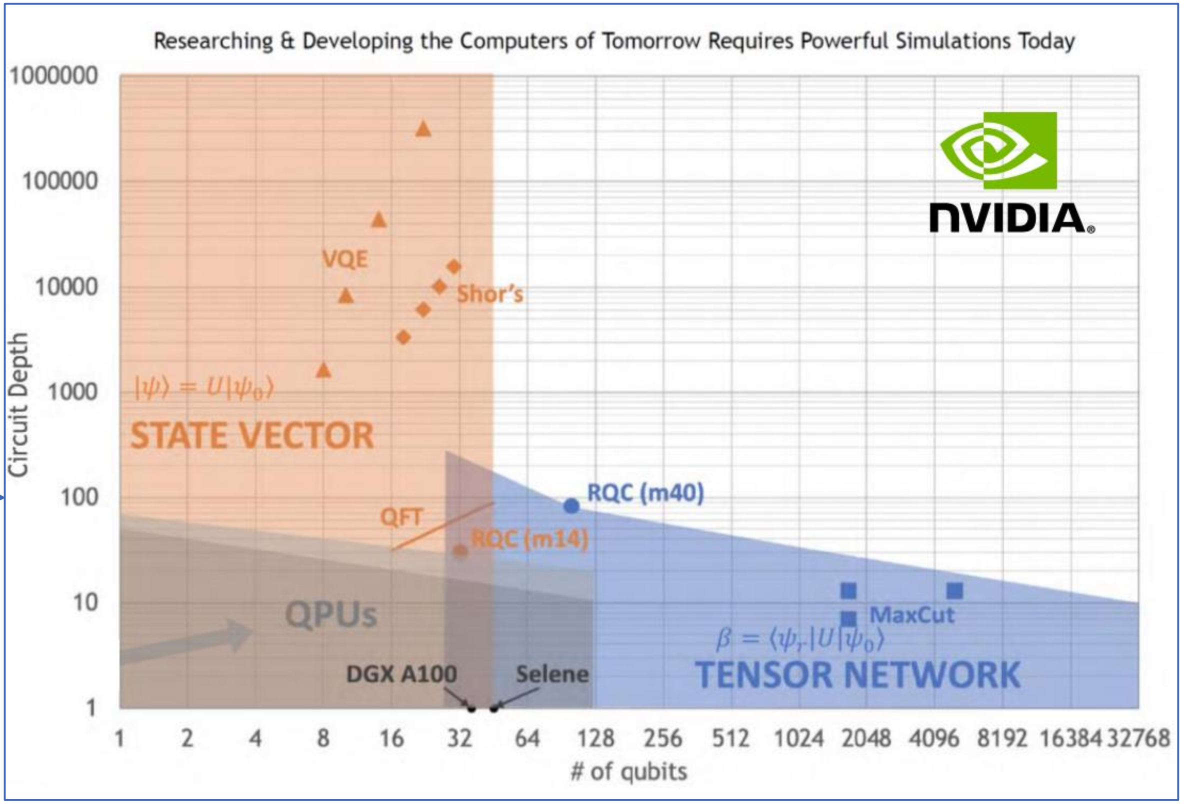
Qubit technologies



https://arxiv.org/ftp/arxiv/papers/2305/2305.09518.pdf

Qubit technologies





https://arxiv.org/ftp/arxiv/papers/2305/2305.09518.pdf

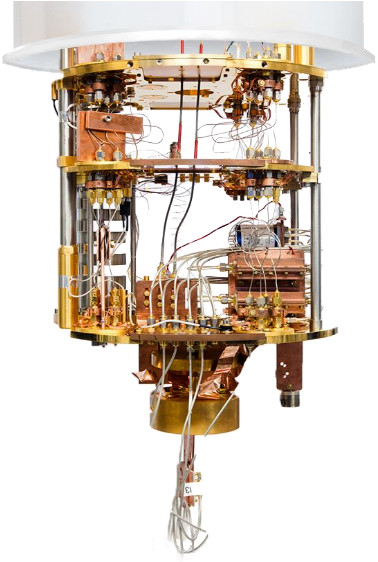
CINECA QUANTUM COMPUTING LAB

The NISQ Era

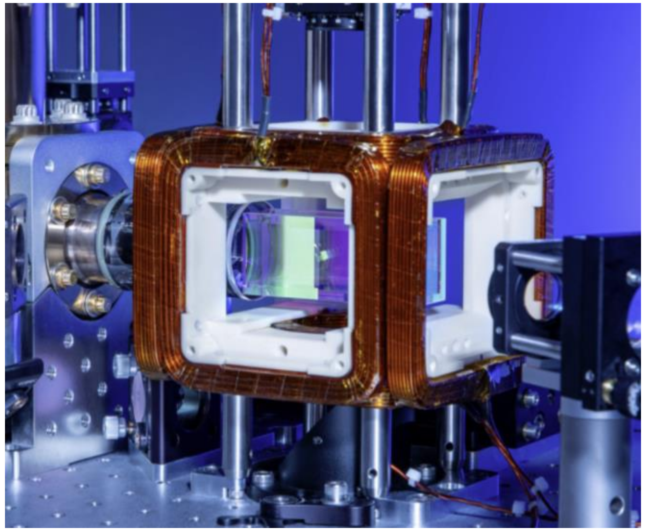
NISQ = Noisy Intermediate-Scale Quantum

Intermediate-Scale Quantum computers with no error correction

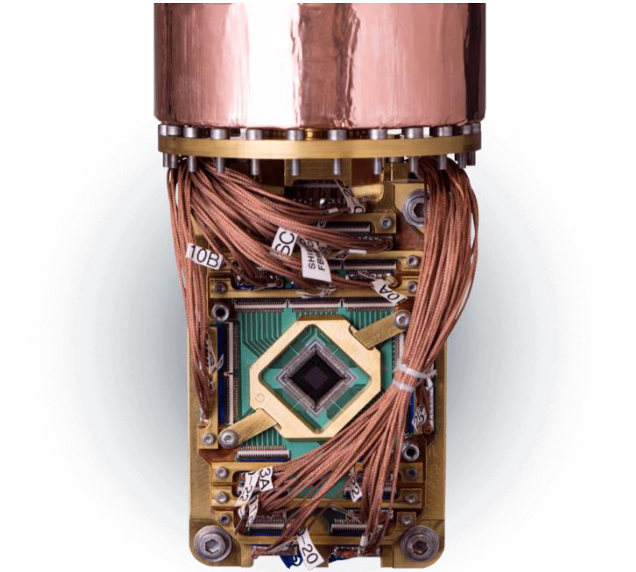
General Purpose QC



Quantum Simulator

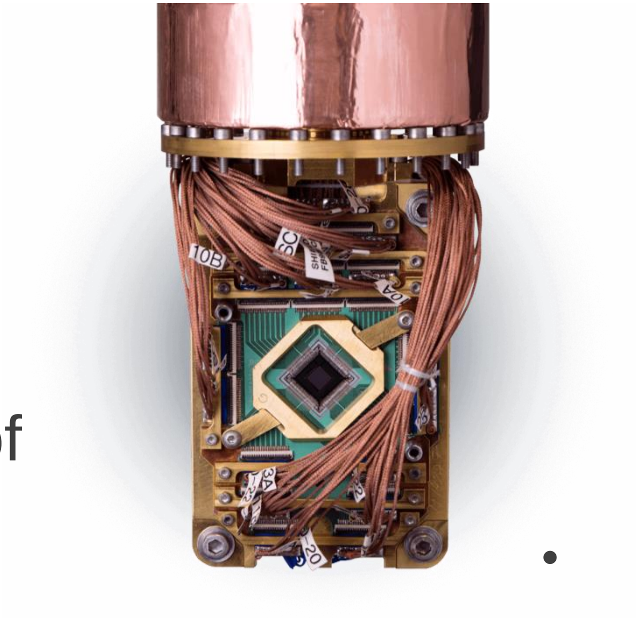


Quantum Annealers



The NISQ Era

Quantum Annealers



Can only run Quantum annealing algorithm

Intermediate-Scale:

Up to several thousands of qubits

D-Wave Advantage: 5000 qubits

D-Wave The Quantum Computing Company™

Noise:

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

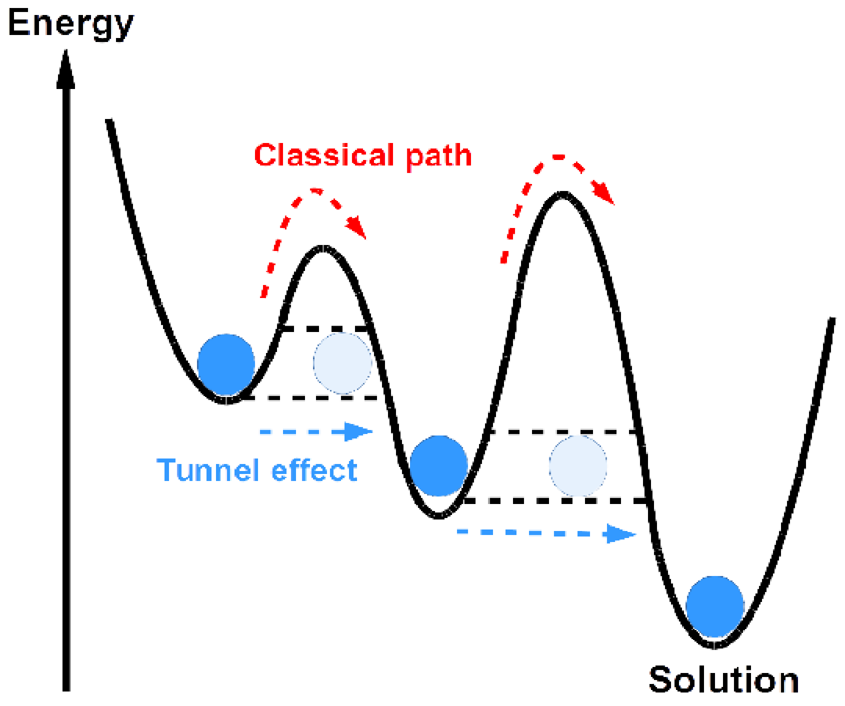
The NISQ Era

Quantum Annealers

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

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

- **Use Quantum Tunnelling and Superposition to explore the configuartion space**



Quantum Tunnelling

Catherine C. McGeoch, *Adiabatic Quantum Computation and Quantum Annealing: Theory and Practice* , Morgan & Claypool, 2014.

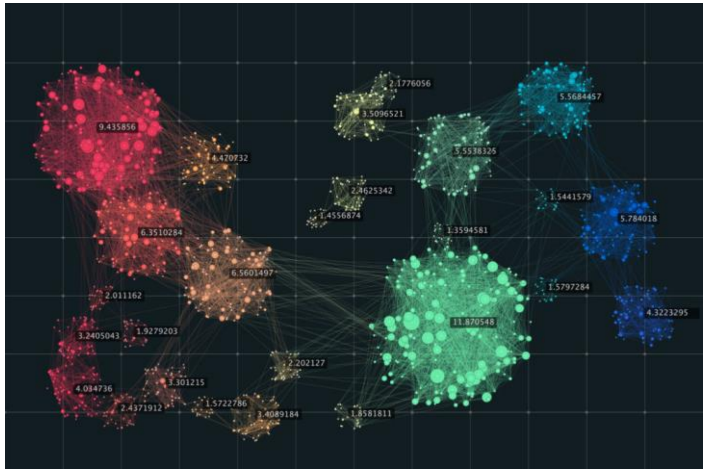
The NISQ Era

Quantum Annealers

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

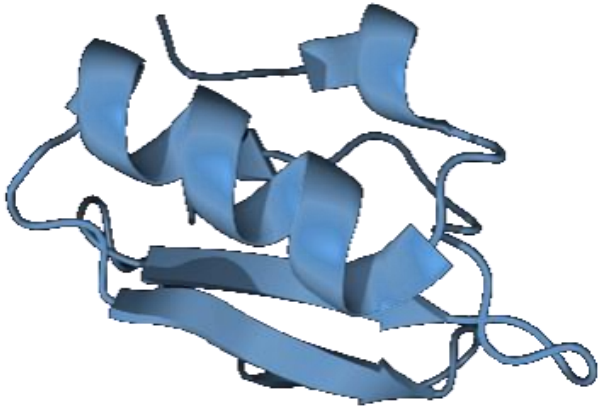
Ising formulation of NP problems:
https://arxiv.org/abs/1302.5843

Machine Learning



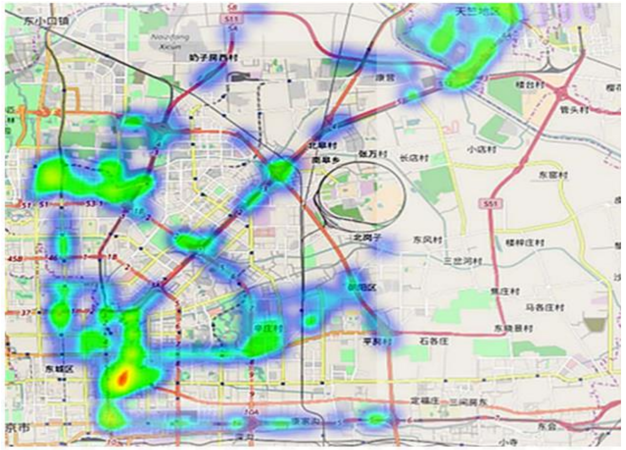
https://arxiv.org/abs/1906.06283

Molecular Dynamics



https://arxiv.org/abs/2107.13607

Scheduling



https://arxiv.org/abs/2006.14162

Quantum Annealers

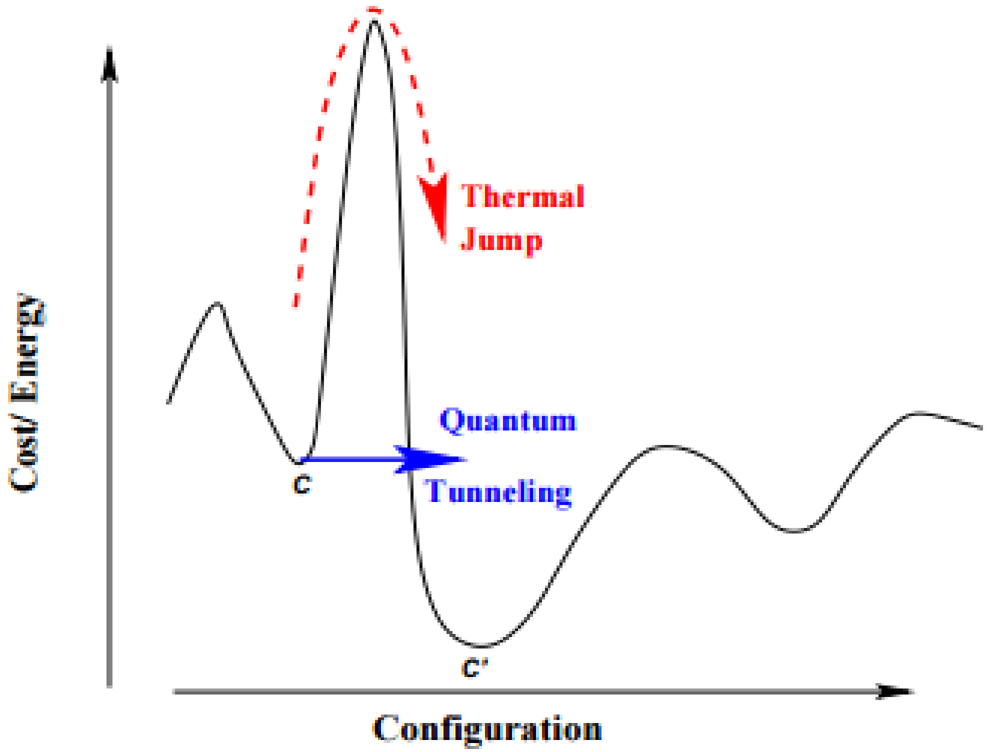
- **Could have advantage over classical techniques like Simulated Annealing**

The transition probability in SA is proportional to

$$e^{-\frac{\Delta}{k_B T}}$$

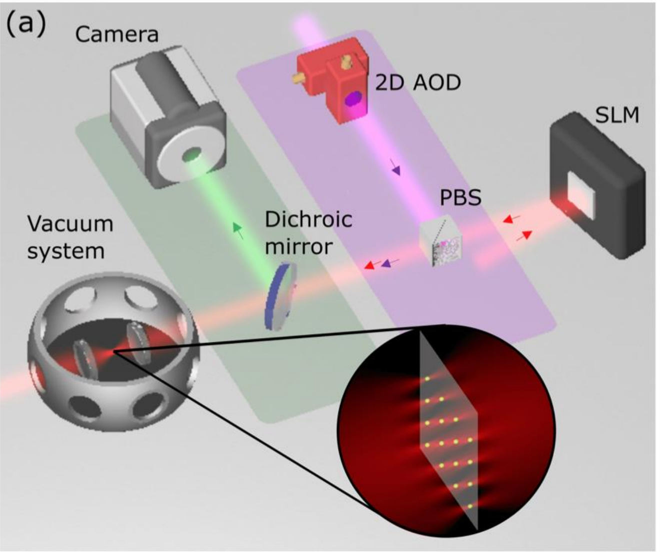
In QA, the strength of transverse field determines the probability of quantum tunneling. The transition probability is proportional to

$$e^{-\frac{\sqrt{\Delta} w}{\Gamma}} \quad \text{with} \quad w \ll \sqrt{\Delta}$$

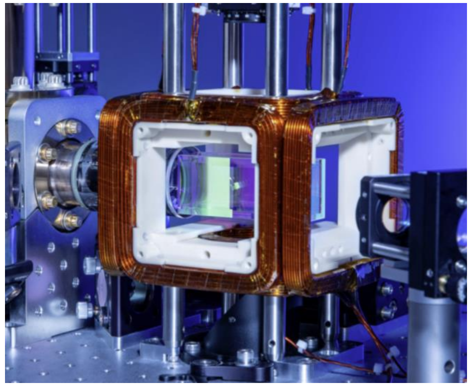


Catherine C. McGeoch, *Adiabatic Quantum Computation and Quantum Annealing: Theory and Practice* , Morgan & Claypool, 2014.

The NISQ Era

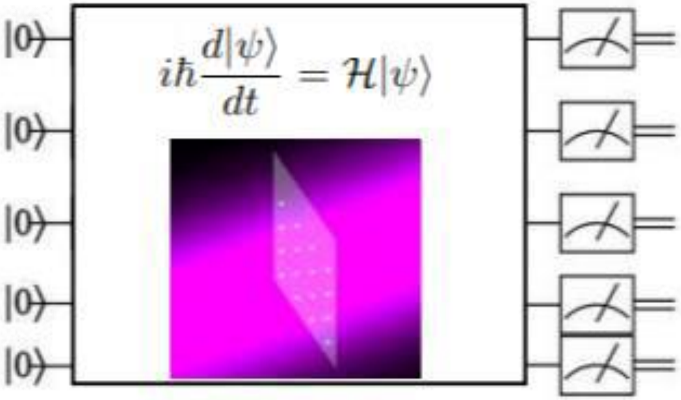


Quantum Simulator



Quantum computing is carried out by **directly manipulating** the mathematical operator (**Hamiltonian**) that **describes the evolution** of the **quantum system**

Analog processor



$$H = \sum_i \frac{\hbar}{2}\left(\Omega(t)\sigma_i^x - \delta(t)\sigma_i^z\right) + \sum_{i<j} U_{ij}\hat{n}_i\hat{n}_j$$

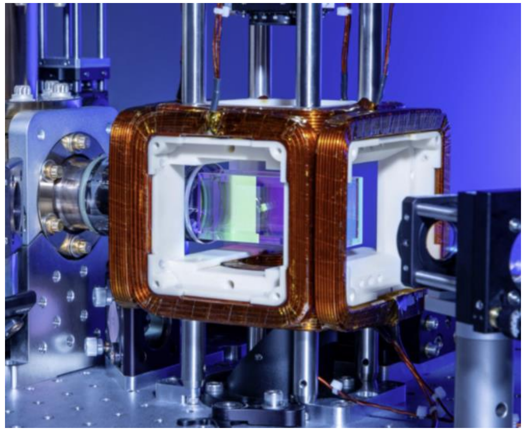
Possible by **varying**:

- **Intensity** and **frequency** of lasers used to manipulate quantum state
- Qubit register **topology**

https://arxiv.org/abs/2006.12326

The NISQ Era

Quantum Simulator



Can implement a limited set of algorithms

Intermediate-Scale :

Up to hundreds of qubits

Pasqal: 100 Qubits
QuEra: 200 Qubits

PASQAL

|QuEra⟩
COMPUTING INC.

Noise:

- **No Quantum Error Correction**: overhead in number of qubit
- **Interaction with environment generates errors, this limits the duration of quantum computation**

The NISQ Era

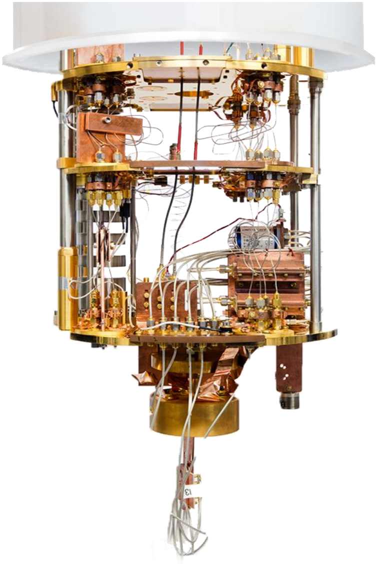
General Purpose QC

Use gates, in theory can run any quantum algorithm

Intermediate-Scale :

Up to hundreds of qubits

IBM: 127 Qubits
Google: 72 Qubits



IBM **Q**

Google AI Quantum

Noise:

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

Quantum algorithms for NISQ Devices

NISQ-ready algorithms

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

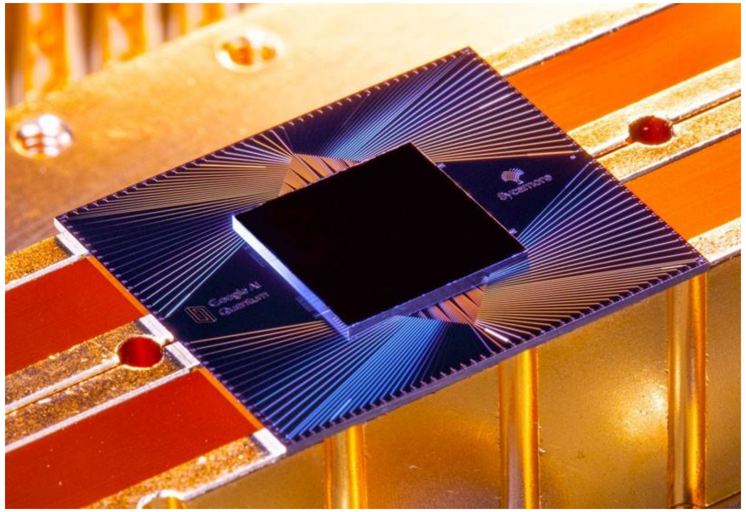
- **Speed up**
- **Better quality solutions**
- **Lower energy consumption**

- **Quantum Chemistry**
- **Quantum Optimization**
- **Quantum AI/Machine Learning**

Beyond quantum supremacy:
https://www.nature.com/articles/d41586-019-02936-3

Quantum algorithms for NISQ Devices

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

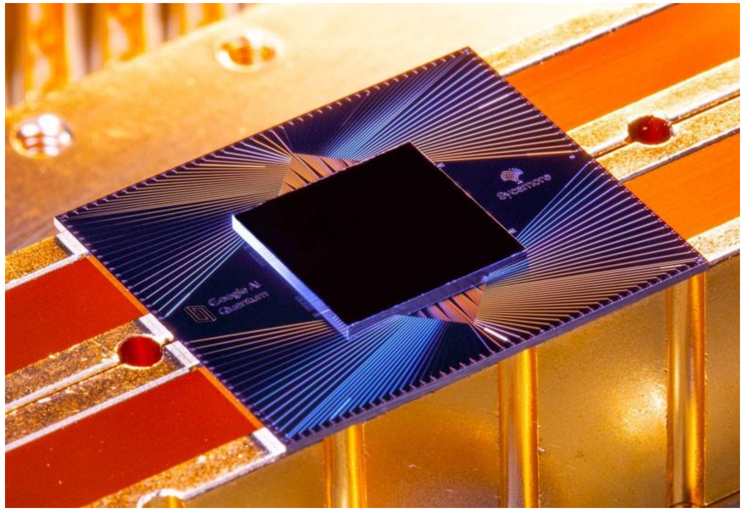


In 2019, researchers at the Google Quantum AI Lab compared the performance of quantum computers to classical supercomputers, using their **Sycamore quantum computer** with **53 qubits.**

https://www.nature.com/articles/s41586-019-1666-5

Quantum algorithms for NISQ Devices

Quantum Supremacy: with just 53 qubits, their **Sycamore quantum computer** was able to **run** a specific algorithm, called the **Random Quantum Circuit (RQC), in 200 seconds. Much less than the 2.5 days estimated to perform the same calculation with most powerful supercomputer.**



VS

https://www.nature.com/articles/s41586-019-1666-5

Quantum algorithms for NISQ Devices

NASA and Google researchers, used a program called **qFlex**, believed to be the most efficient **classic emulator** quantum system to **implement the RQC** algorithm on one of the most powerful **supercomputers in the world**, **Summit**.

Sycamore

Lamp for few hours = 0.42KWh

VS

Summit

21MWh = 5 families for 1 year

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

https://arxiv.org/abs/1811.09599

NISQ-ready algorithms

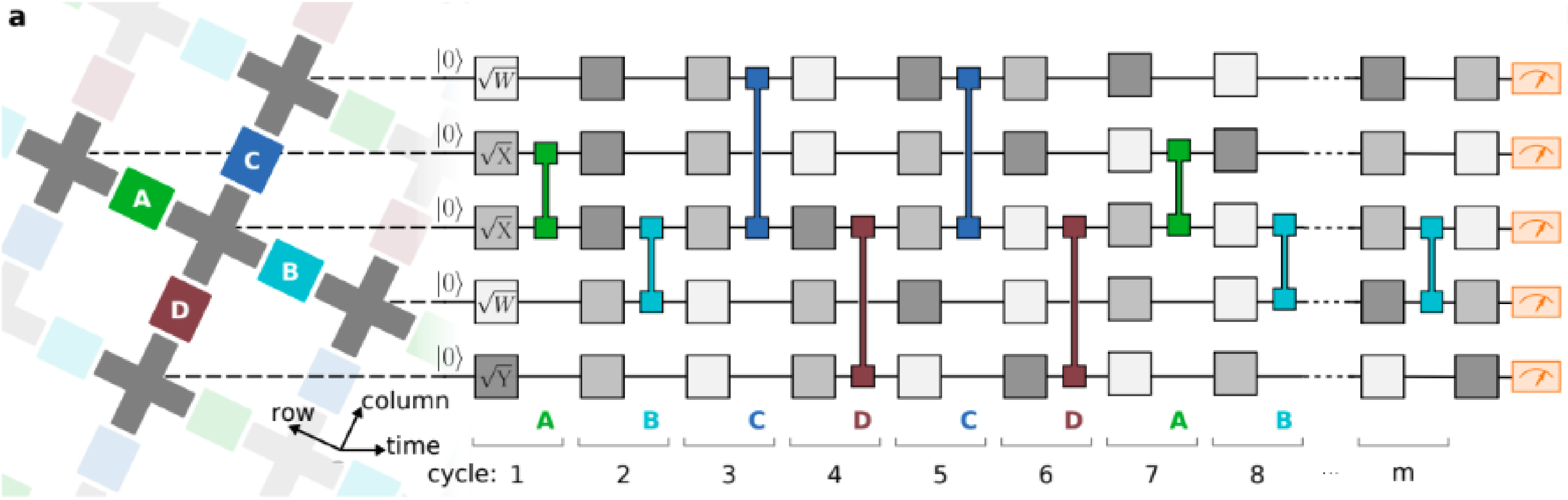
The **scientific community** believes that **NISQ technology** could **outperform traditional classical computers** for **specific applications**

- **Speed up**
- **Better quality solutions**
- **Lower energy consumption**

- **Quantum Chemistry**
- **Quantum Optimization**
- **Quantum AI/Machine Learning**

Quantum algorithms for NISQ Devices

Random Quantum Circuit (RQC) does not solve any useful (real-world) problem.
Its purpose is exactly to prove Quantum supremacy

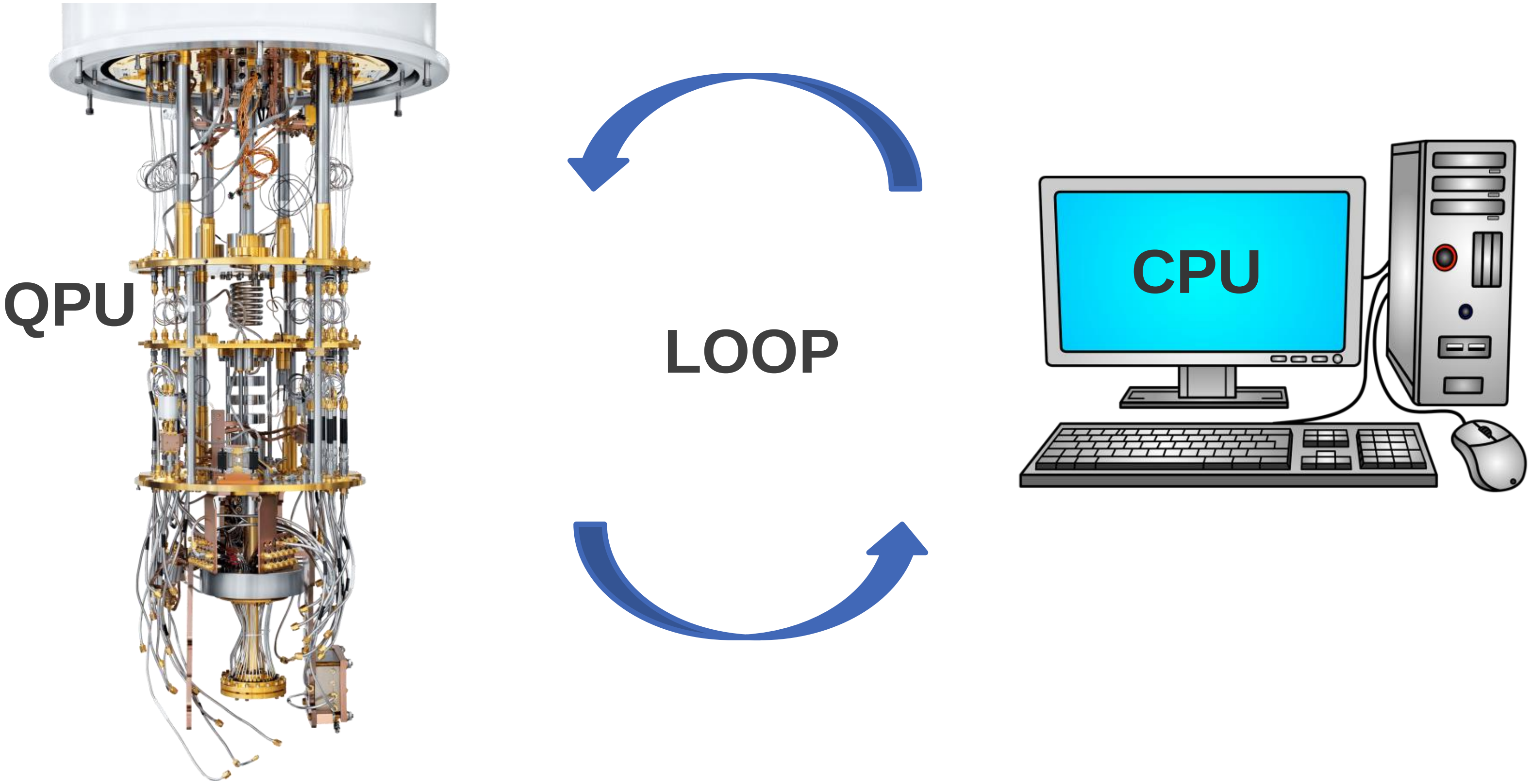


RQC

Real World Problems?

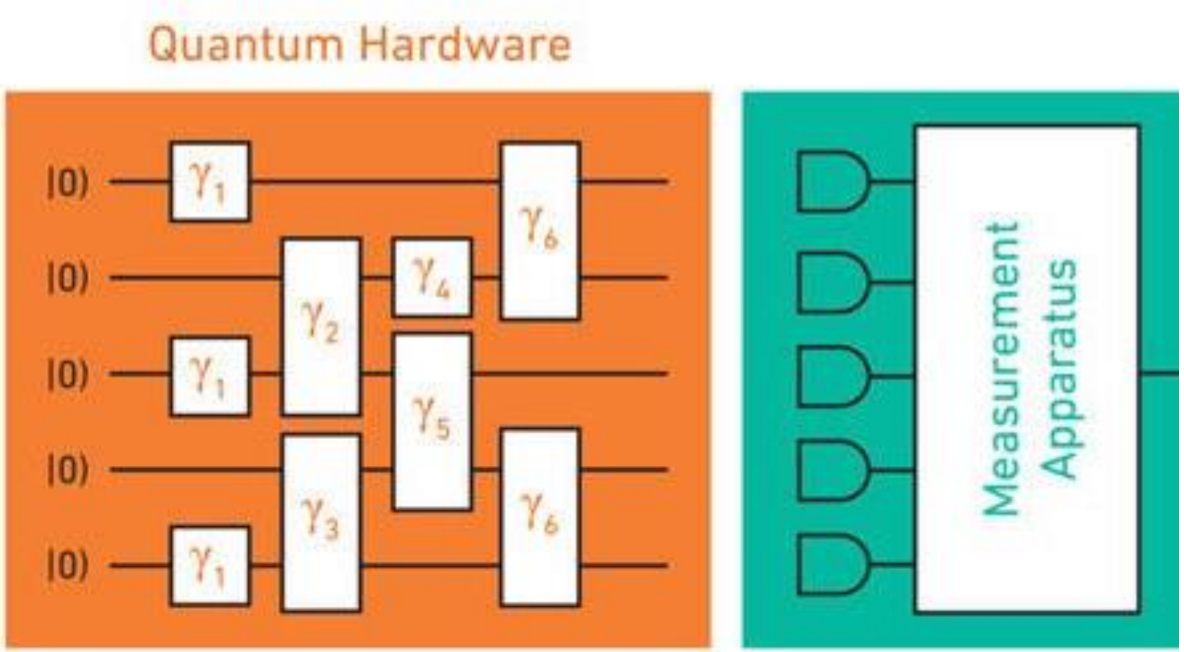
Quantum algorithms for NISQ Devices

Hybrid Quantum-Classical algorithms



Variational Quantum Algorithms:
https://arxiv.org/abs/2012.09265

Parametric Quantum Circuits



- Circuits that **use gates**, or in general, that apply **parameter-dependent operations** to qubits (e.g. Arbitrary rotations of angle γ)
- **Shallow circuits**, i.e. of **limited depth** (1000 gates maximum, due to limited coherence times)
- Circuits in which the **error is not corrected**

→ But **errors can be mitigated**
https://arxiv.org/abs/2009.04417

Working principle

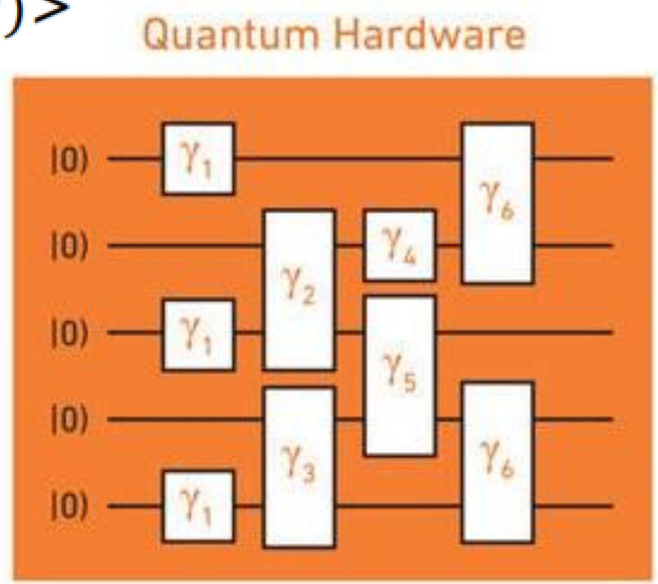
Variational Quantum Algorithms:
https://arxiv.org/abs/2012.09265

Working principle

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

2. Implement Variational Ansatz on the QPU

$|\Psi(\vec{\theta})>$



Variational Quantum Algorithms:
https://arxiv.org/abs/2012.09265

Working principle

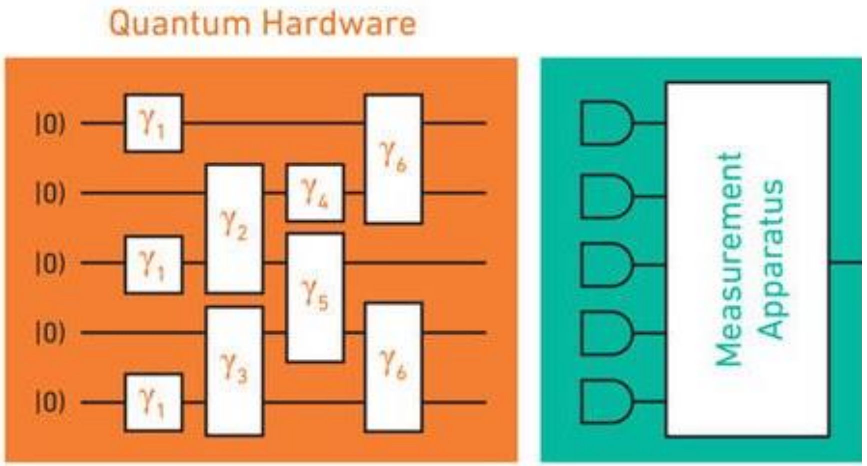
1. Choose the parametric circuit you want to use (Variational Ansatz)

2. Implement Variational Ansatz on the QPU

$$|\Psi(\vec{\theta})>$$

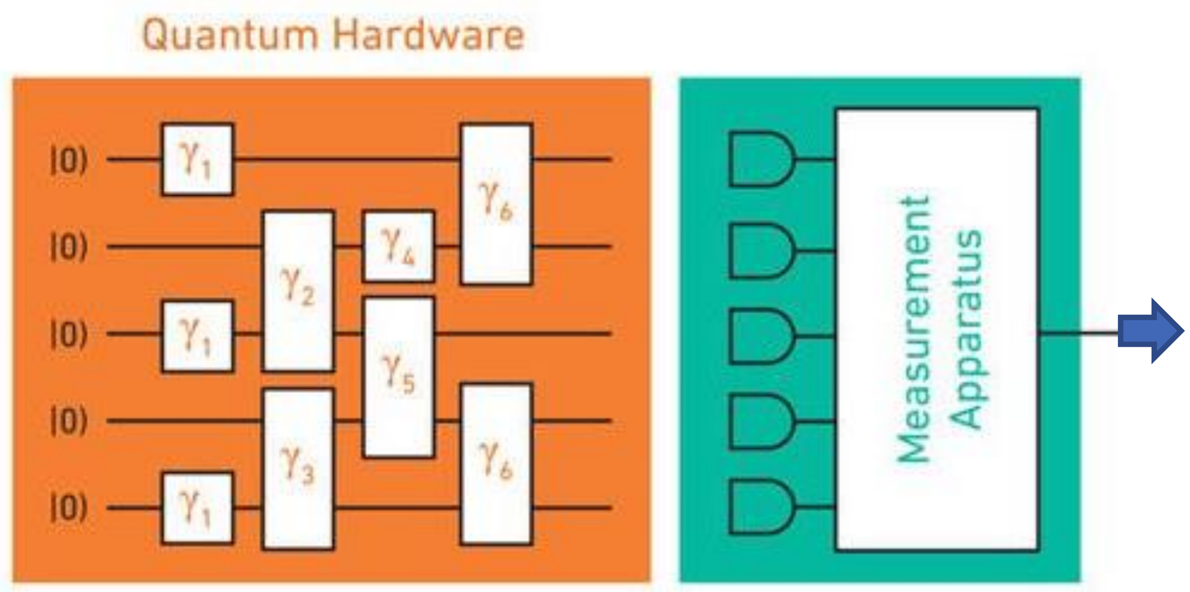
3. Measure the qubits and calculate the cost function

$$E_{\vec{\theta}} = < \Psi(\vec{\theta})|\mathbf{H}|\Psi(\vec{\theta})>$$

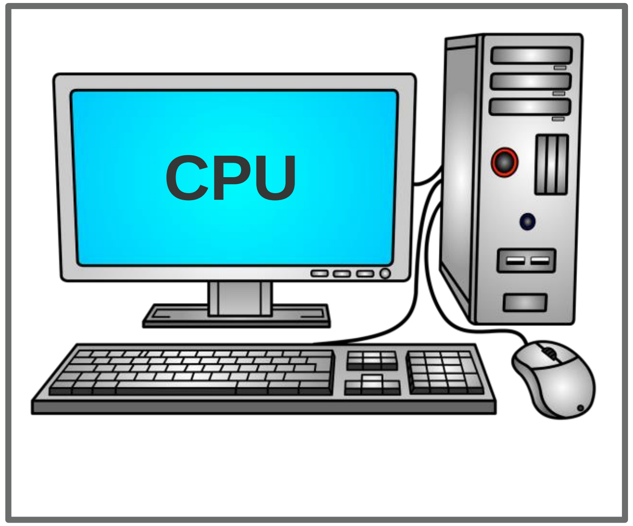


Variational Quantum Algorithms:
https://arxiv.org/abs/2012.09265

Working principle



4. Classical optimization of parameters gamma



Variational Quantum Algorithms: https://arxiv.org/abs/2012.09265

Quantum algorithms for NISQ Devices

Working principle

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

2. **Implement Variational Ansatz on the QPU**

3. **Measure the qubits and calculate the cost function**

4. **Use a classic computer to optimize the circuit parameters**

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

Variational Quantum Algorithms: https://arxiv.org/abs/2012.09265

Working principle

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

2. Implement Variational Ansatz on the QPU

3. Measure the qubits and calculate the cost function

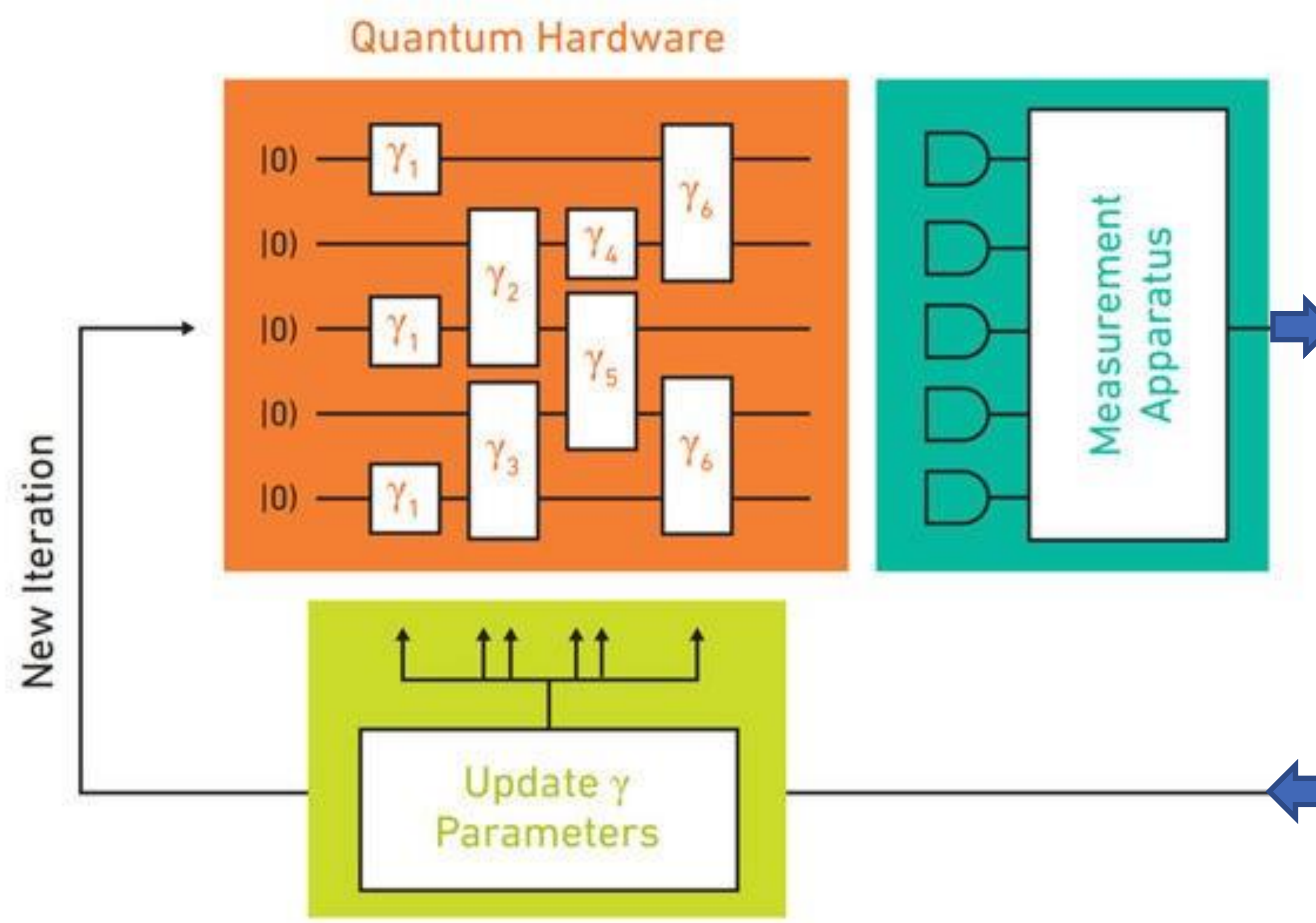
4. Use a classic computer to optimize the circuit parameters

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

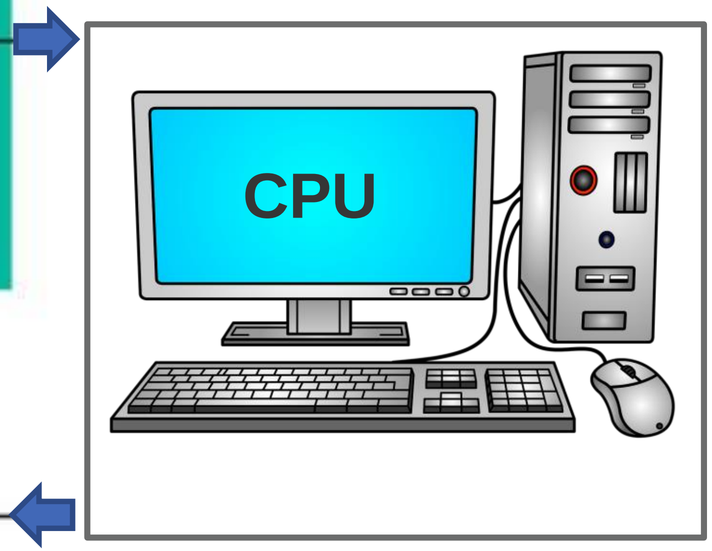
Heuristic Algorithm

Quantum algorithms for NISQ Devices

Working principle



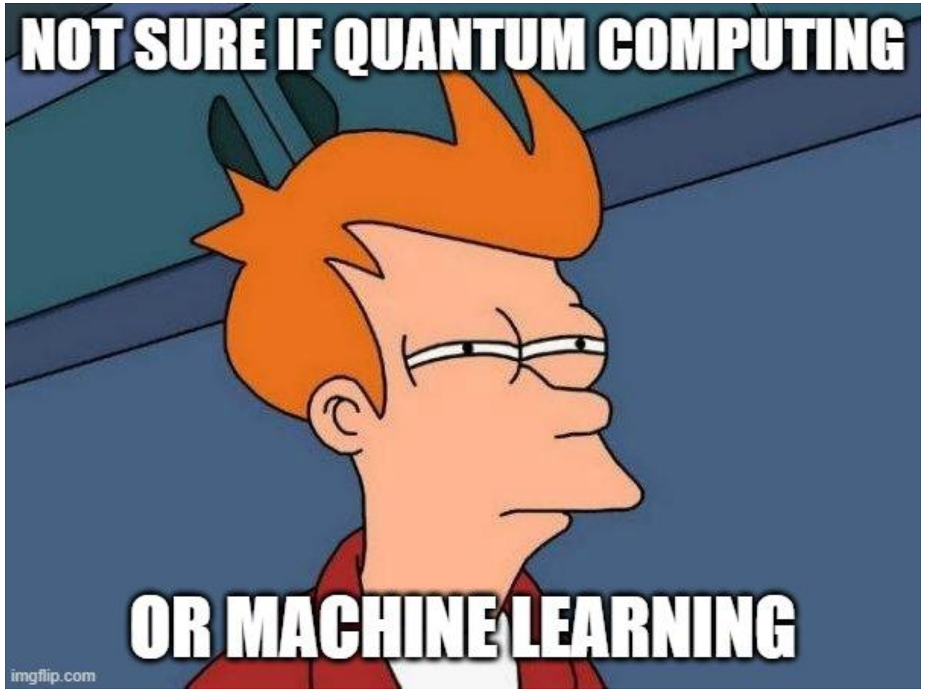
4. Classical optimization of parameters gamma

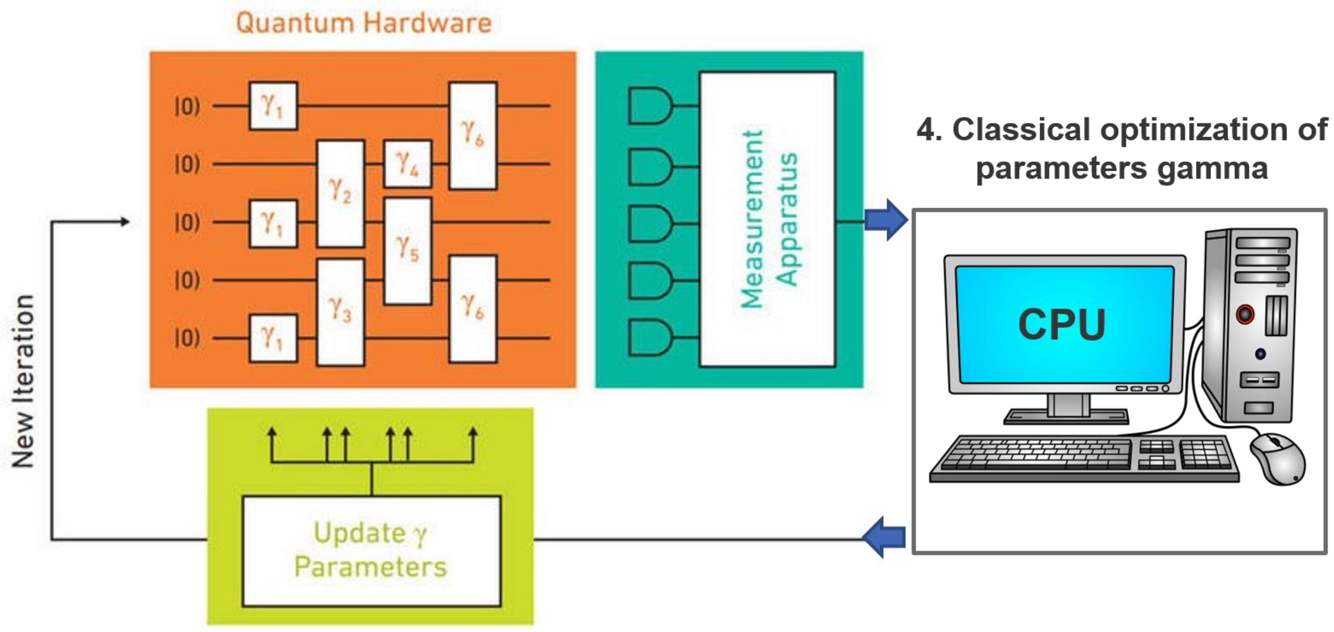


Variational Quantum Algorithms:
https://arxiv.org/abs/2012.09265

Quantum algorithms for NISQ Devices

Working principle

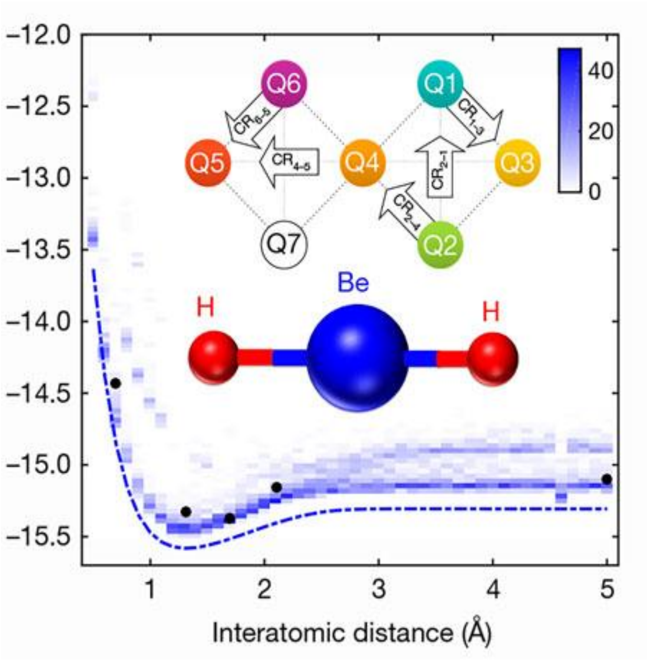




Variational Quantum Algorithms:
https://arxiv.org/abs/2012.09265

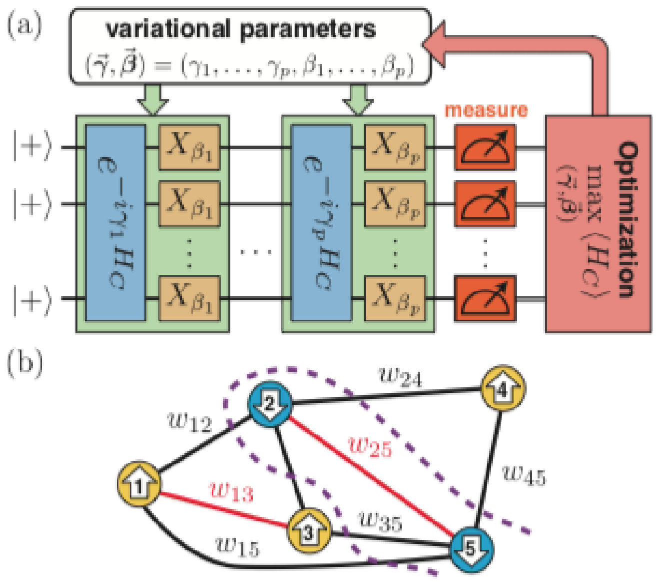
Quantum algorithms for NISQ Devices

VQE



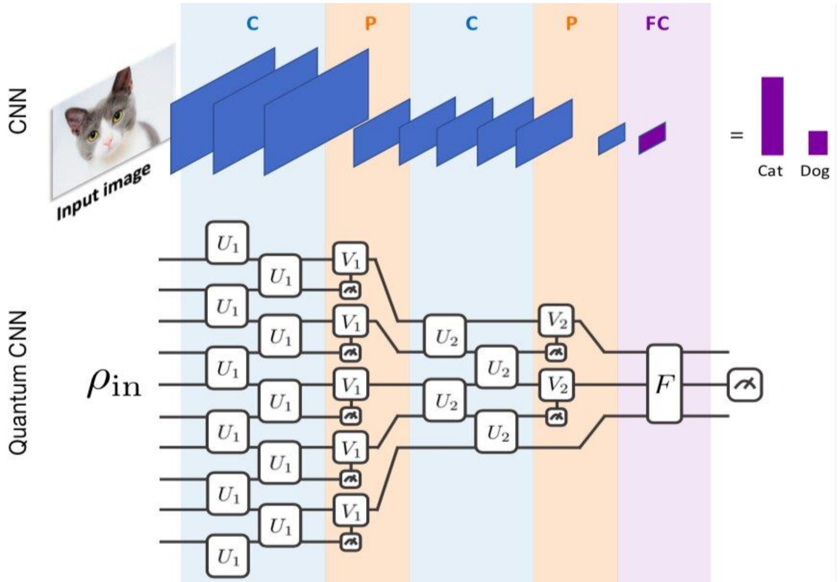
Quantum Chemistry

QAOA



Quantum Optimization

QSVM & QNN



Quantum Machine Learning

Quantum algorithms for NISQ Devices: General Purpose QC

VQE

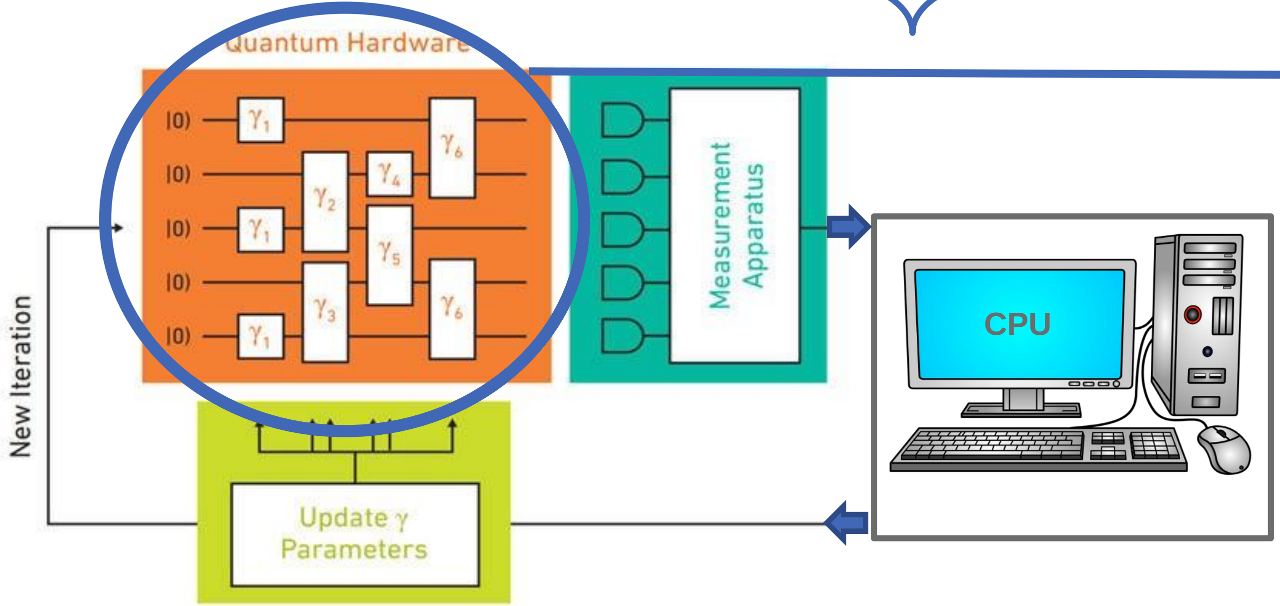
Quantum Chemistry

QAOA

Quantum Optimization

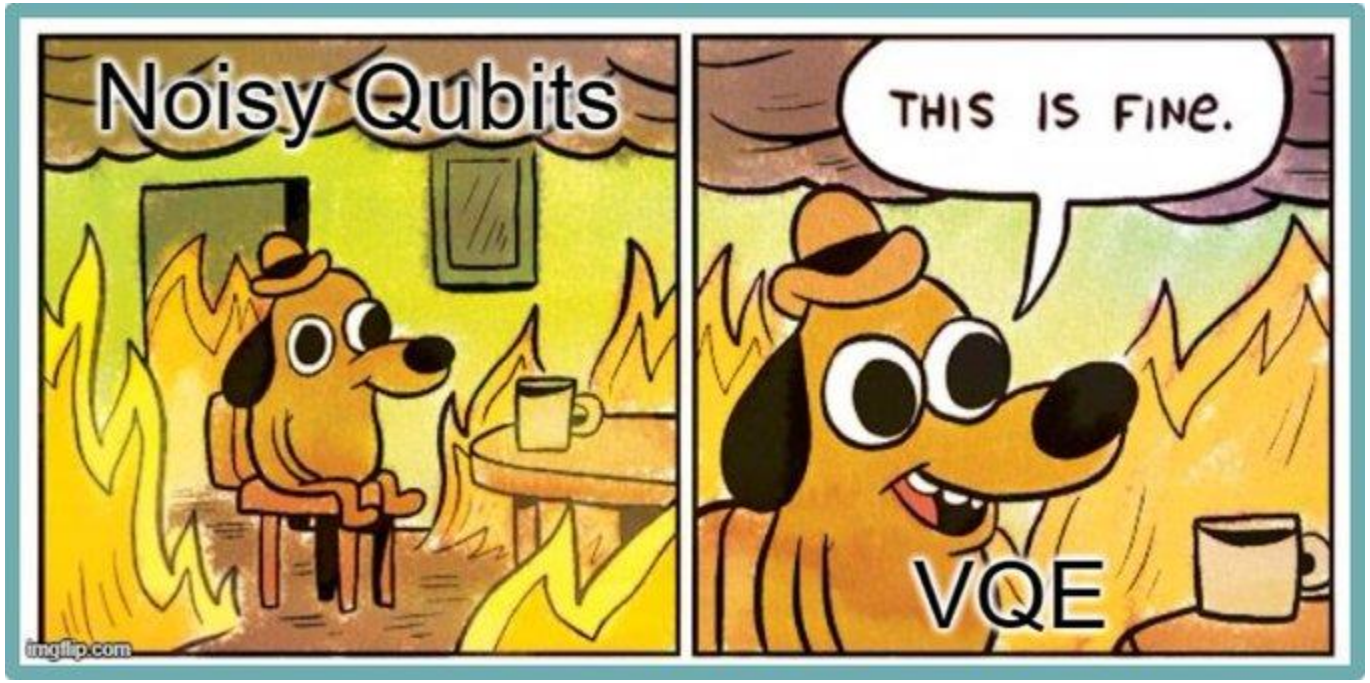
QSVM & QNN

Quantum Machine Learning



The **main difference** between **VQE, QAOA** and **QML** concerns the **choice of the parametric quantum circuit** (Variational Ansatz)

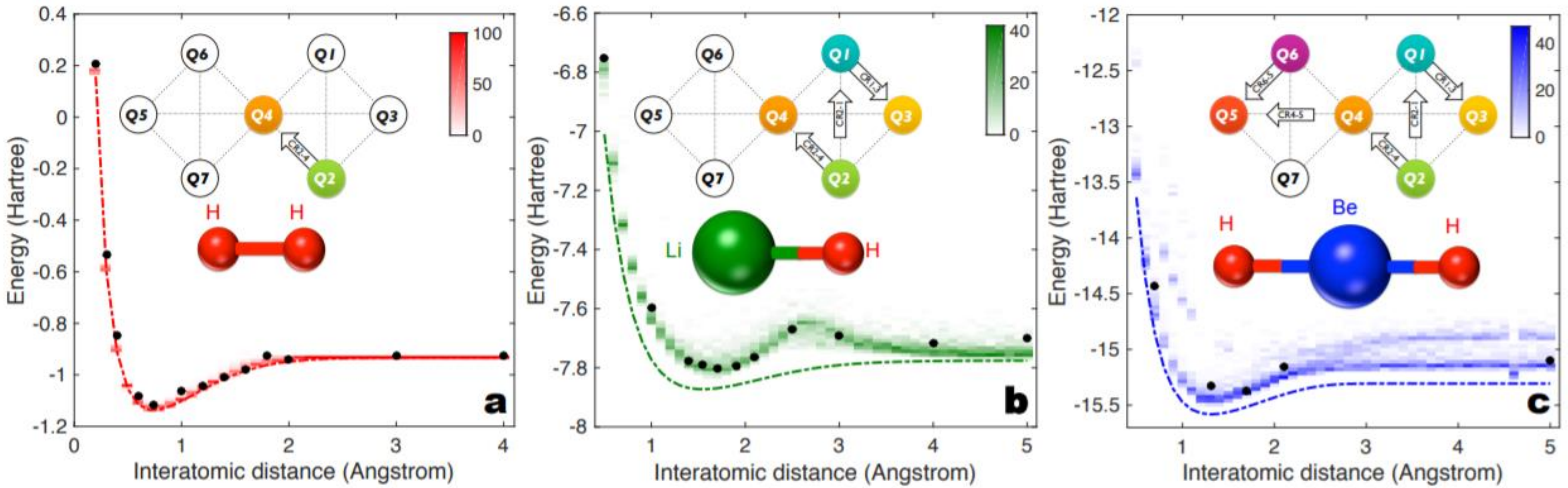
Variational Quantum Eigensolver (VQE)



https://arxiv.org/abs/2011.01125

Variational Quantum Eigensolver (VQE) – QUANTUM CHEMISTRY

Objective: finding the ground state energy of molecules



https://arxiv.org/abs/2011.01125

Variational Quantum Eigensolver (VQE) – QUANTUM CHEMISTRY

<u>**Objective**</u>:

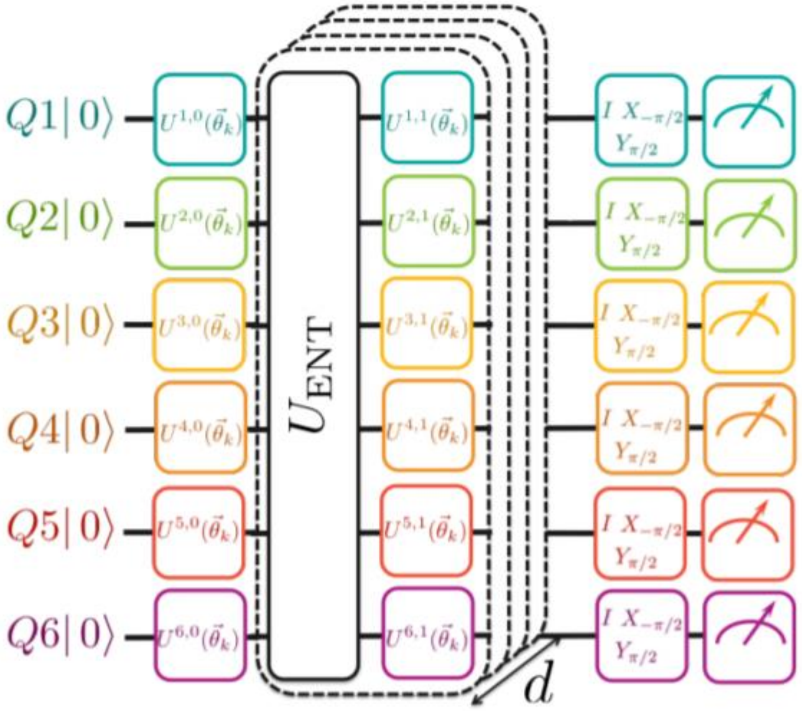
to **calculate the ground state of molecules**

<u>**Method**</u>:

Ansatz is a provisional molecular ground state

<u>**Possible Advantage**</u>:

Simulate complex quantum molecular wavefunctions in polynomial time

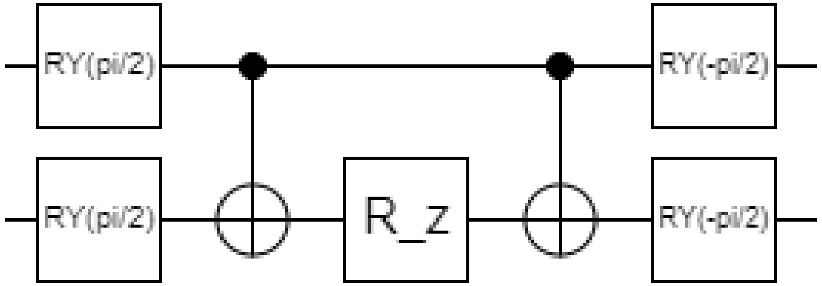


https://arxiv.org/abs/1704.05018

Quantum algorithms for NISQ Devices

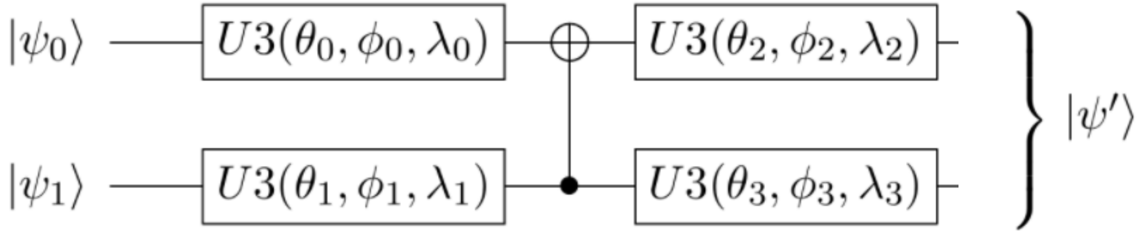
Variational Quantum Eigensolver (VQE) – Ansatz

VQE uses:



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

(**<u>Challenge</u> :** may be harder to implement on real hardware)

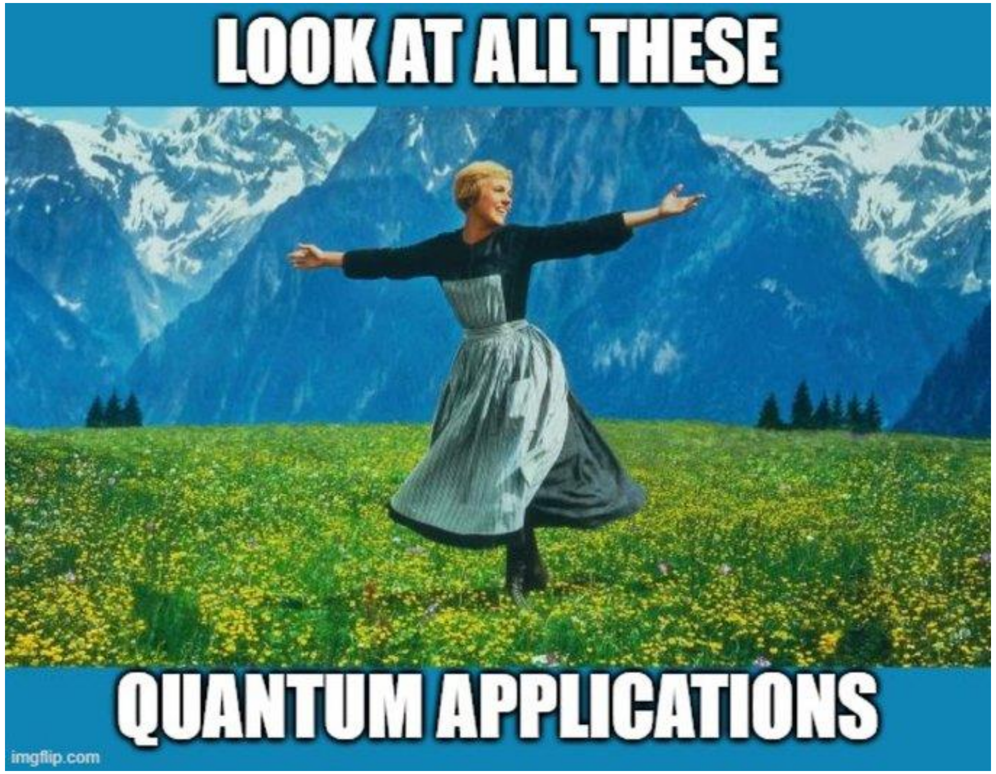


or a **Hardware-efficient Ansatz**

(**<u>Challenge</u> :** easy to implement on hardware but lack of any physical meaning)

https://arxiv.org/abs/1704.05018

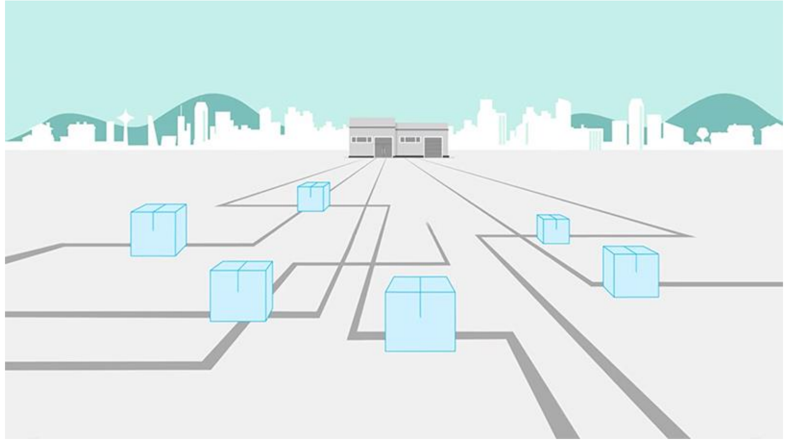
Quantum Approximate Optimization Algorithm (QAOA)



Quantum algorithms for NISQ Devices

Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

Optimization Problems



Routing

Scheduling

Portfolio Optimization

Quantum algorithms for NISQ Devices

Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

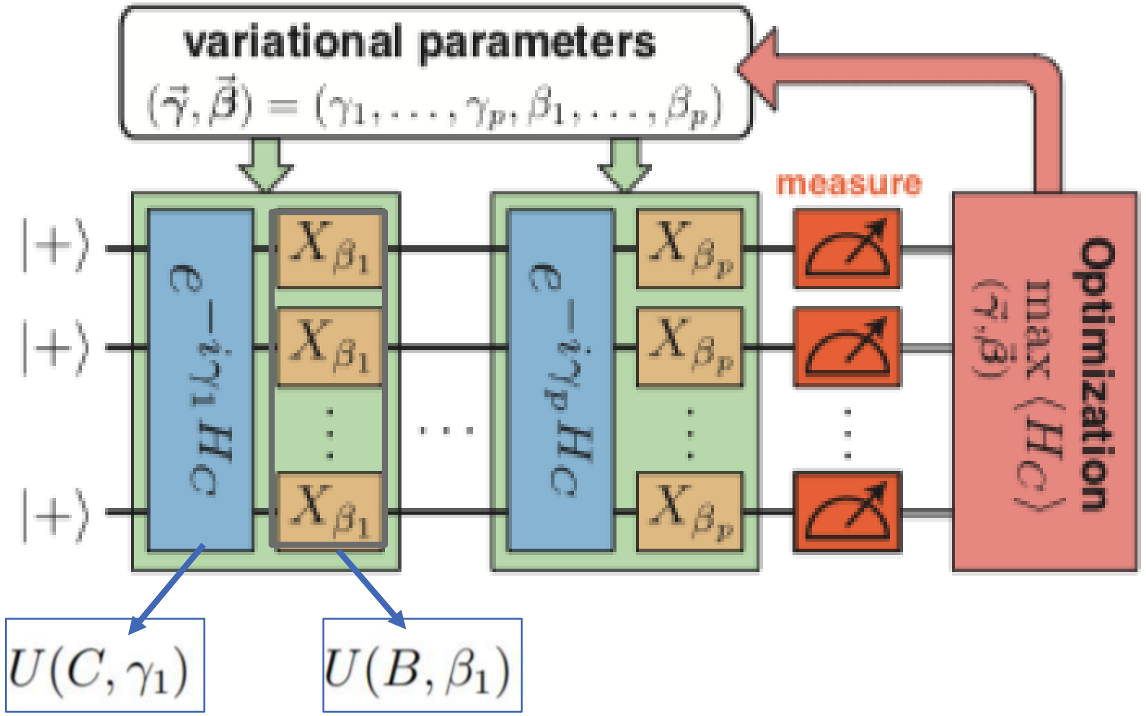
Objective: to **solve a combinatorial optimization problem**

Method: **Ansatz encodes two alternating circuits, U(C) and U(B)**, each **parameterized** by a number, **γ and β**.

Ideally, the circuit provides the **solution |γ,β>** to a **combinatorial problem implicit in** the definition of **U(C)**.

A Quantum Approximate Optimization Algorithm: https://arxiv.org/abs/1411.4028

$$|\boldsymbol{\gamma},\boldsymbol{\beta}\rangle = U(B,\beta_p)U(C,\gamma_p)\cdots U(B,\beta_1)U(C,\gamma_1)\,|s\rangle$$



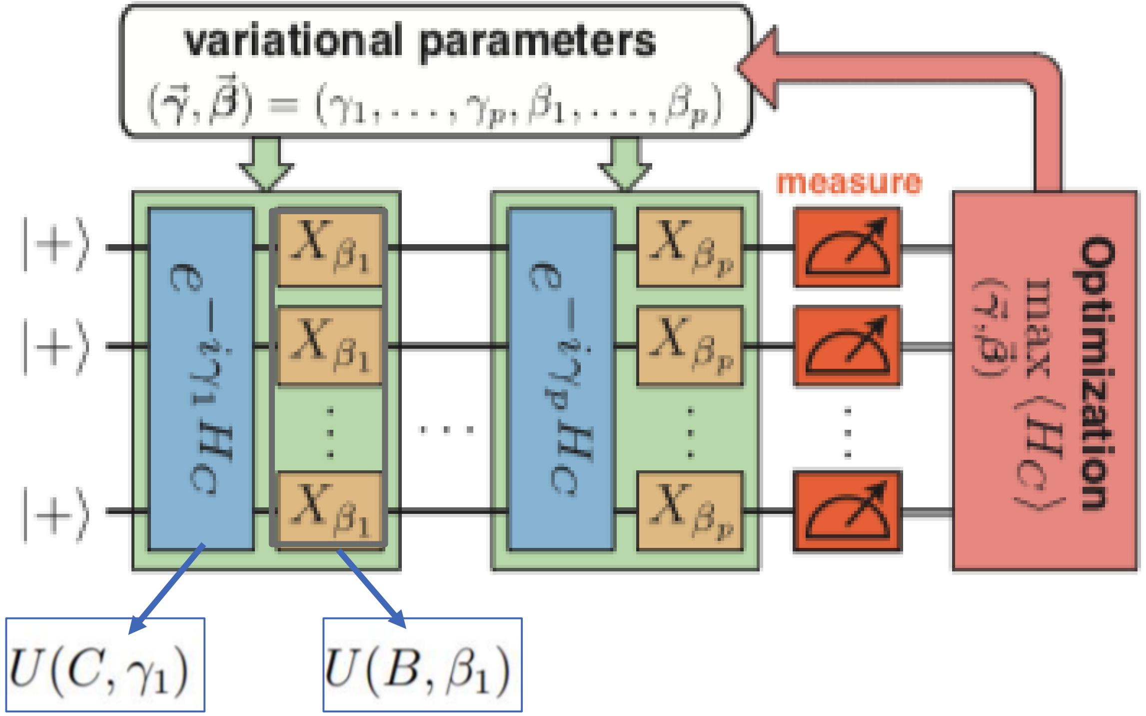
Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

$$\underbrace{|\gamma, \beta\rangle}_{\text{solution}} = \underbrace{U(B,\beta_p)\,U(C,\gamma_p)\cdots U(B,\beta_1)\,U(C,\gamma_1)}_{\text{Circuit (alternating circuits)}}\ \underbrace{|s\rangle}_{\text{initial state}}$$

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

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

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



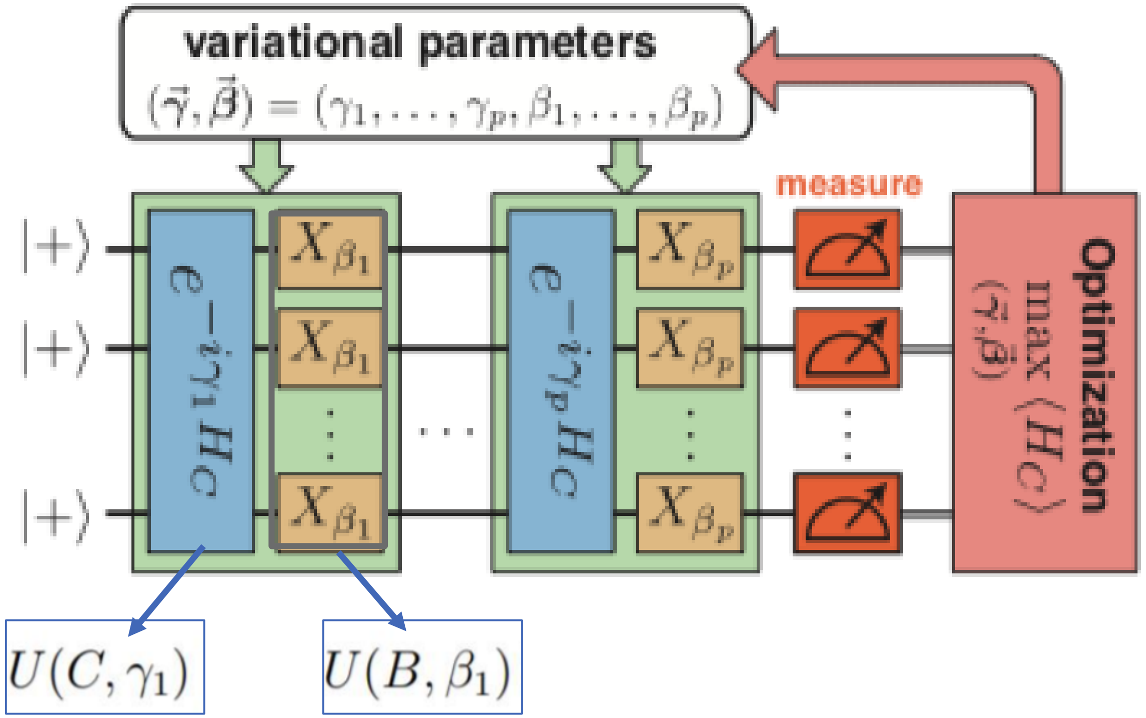
__**Possible Advantage**__:

Allow the **quantum exploration of the solution space**

Quantum algorithms for NISQ Devices

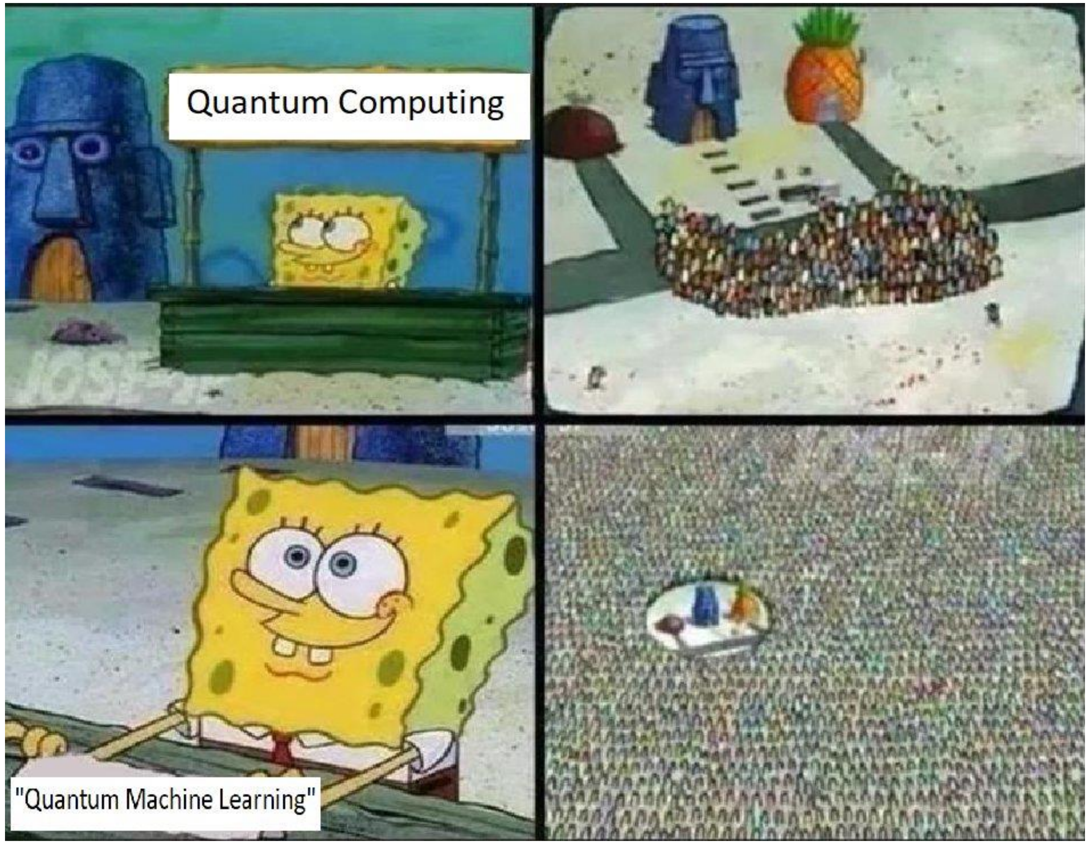
Quantum Approximate Optimization Algorithm (QAOA) – QUANTUM OPTIMIZATION

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



A Quantum Approximate Optimization Algorithm:
https://arxiv.org/abs/1411.4028

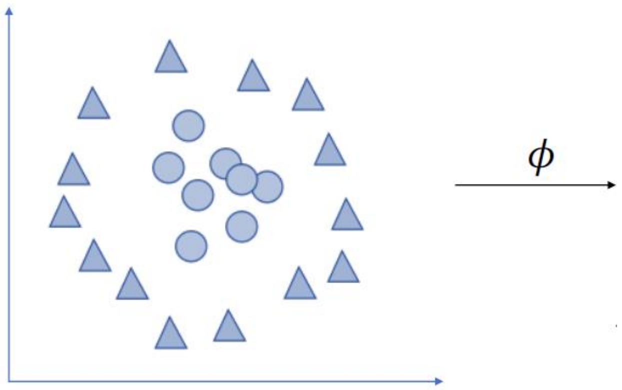
Quantum Machine Learning (QML)

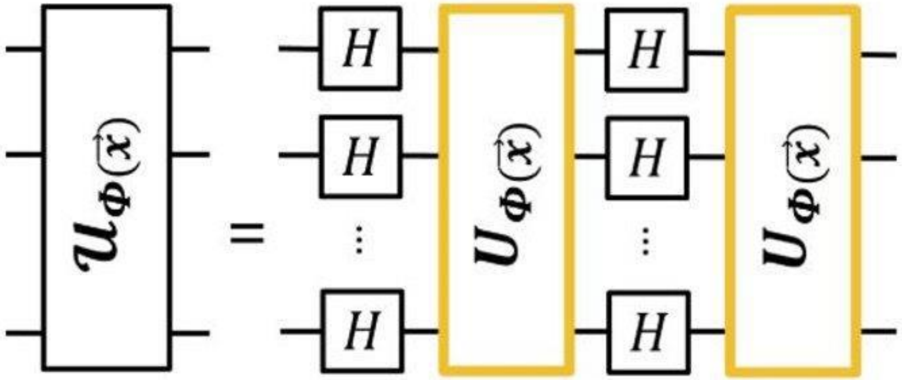


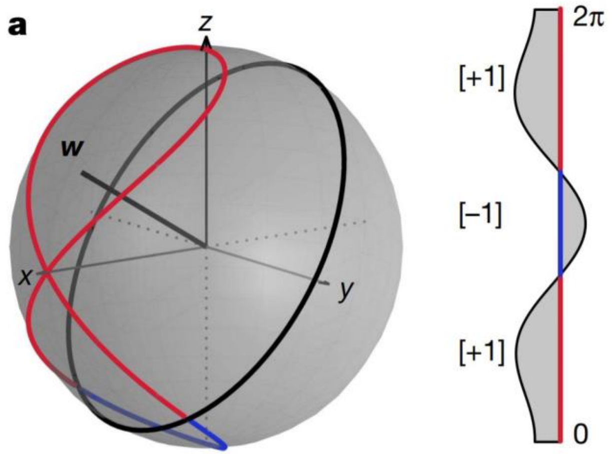
Quantum Machine Learning (QML) – Quantum Feture Map

Quantum Feature map
maps classical vector
into a quantum state

$$\vec{x} \mapsto |\Phi(\vec{x})\rangle = \mathcal{U}_{\Phi(\vec{x})}|0\rangle^{\otimes n}$$







Quantum enhanced feature spaces:
https://arxiv.org/abs/1804.11326

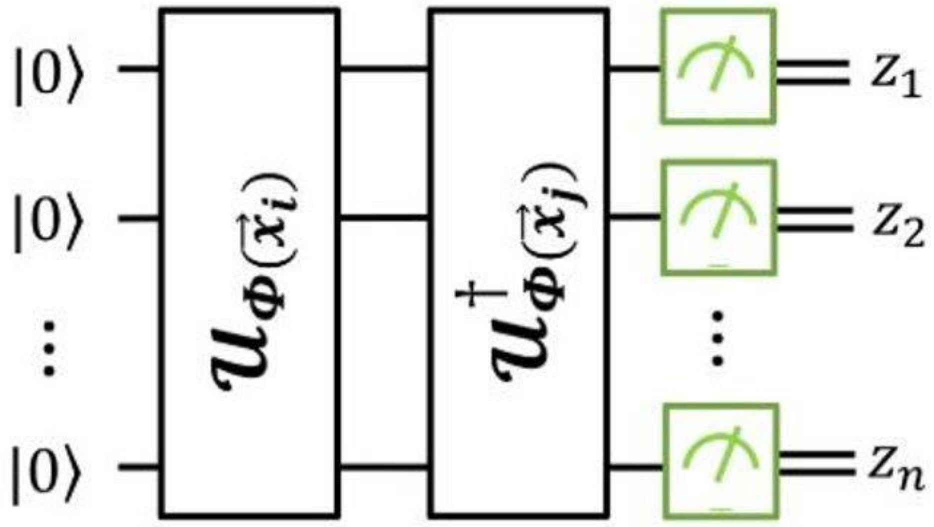
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum SVM

Quantum Kernel ➡

$$K(\vec{x}_i, \vec{x}_j) = \left|\langle \Phi(\vec{x}_i) | \Phi(\vec{x}_j) \rangle\right|^2 = \left|\langle 0 | \mathcal{U}^\dagger_{\Phi(\vec{x}_j)} \mathcal{U}_{\Phi(\vec{x}_i)} | 0 \rangle^{\otimes n}\right|^2$$

<u>**Goal**</u>: Address a classification problem (like classical SVMs)



Challenge: More complex feature map at low computational cost

Quantum enhanced feature spaces:
https://arxiv.org/abs/1804.11326

Quantum algorithms for NISQ Devices

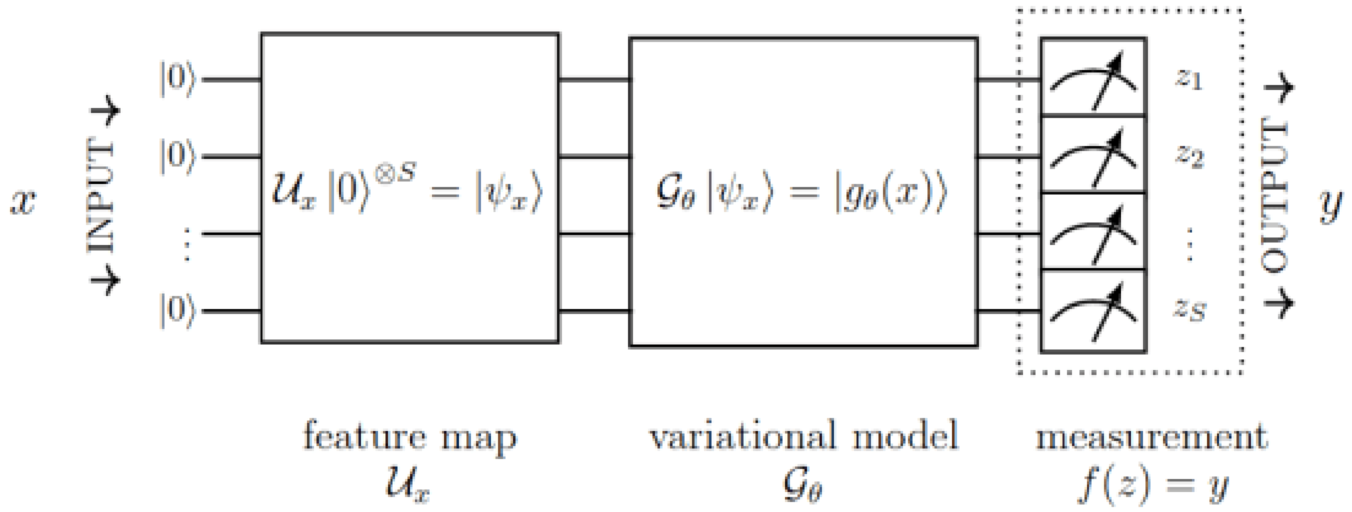
Quantum Machine Learning (QML) – Quantum NN

Goal: Address a supervised machine learning problem

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

The power of quantum neural networks
https://arxiv.org/abs/2011.00027

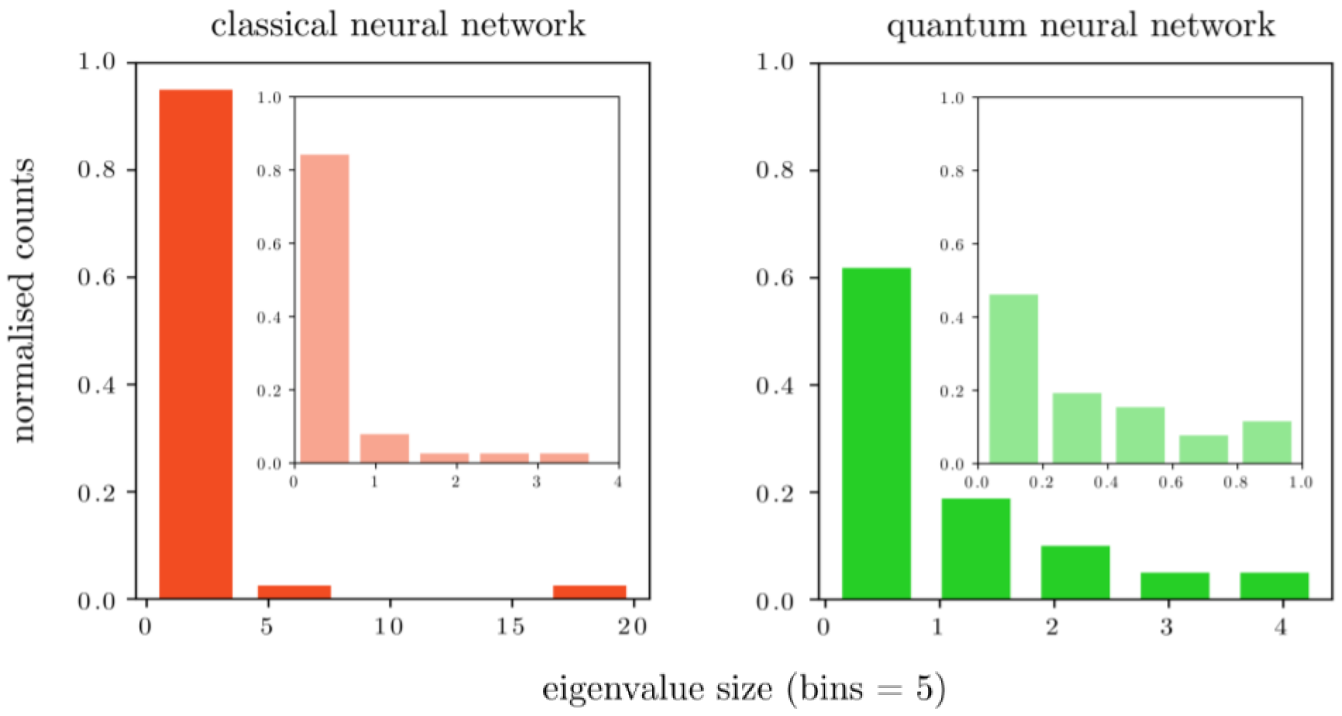
- **Feature map**: Store the inputs in a quantum state
- **Variational circuit**: Learnable parameter circuit
- **Expectation value**: Measurements introduce non-linearity



Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum NN

The Power of QNNs



The power of quantum neural networks
https://arxiv.org/abs/2011.00027

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

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

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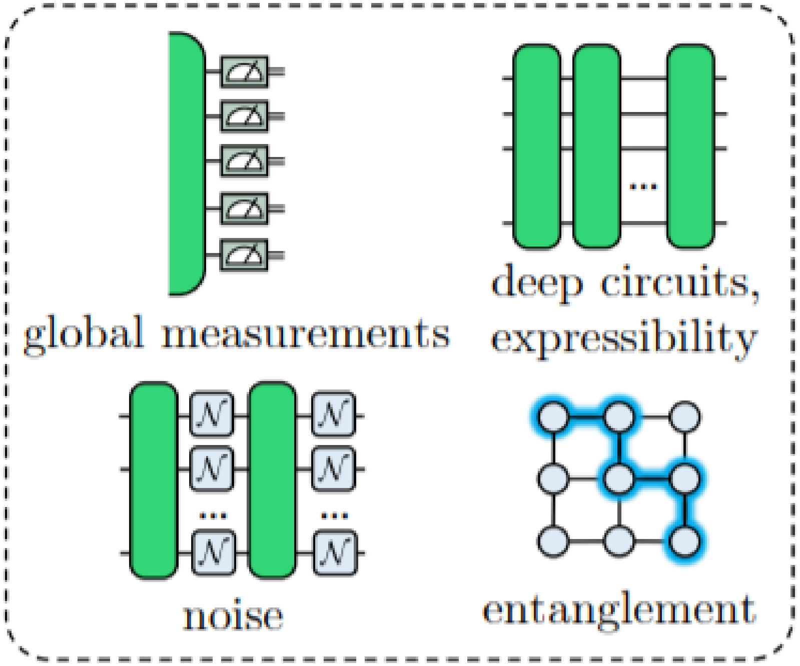
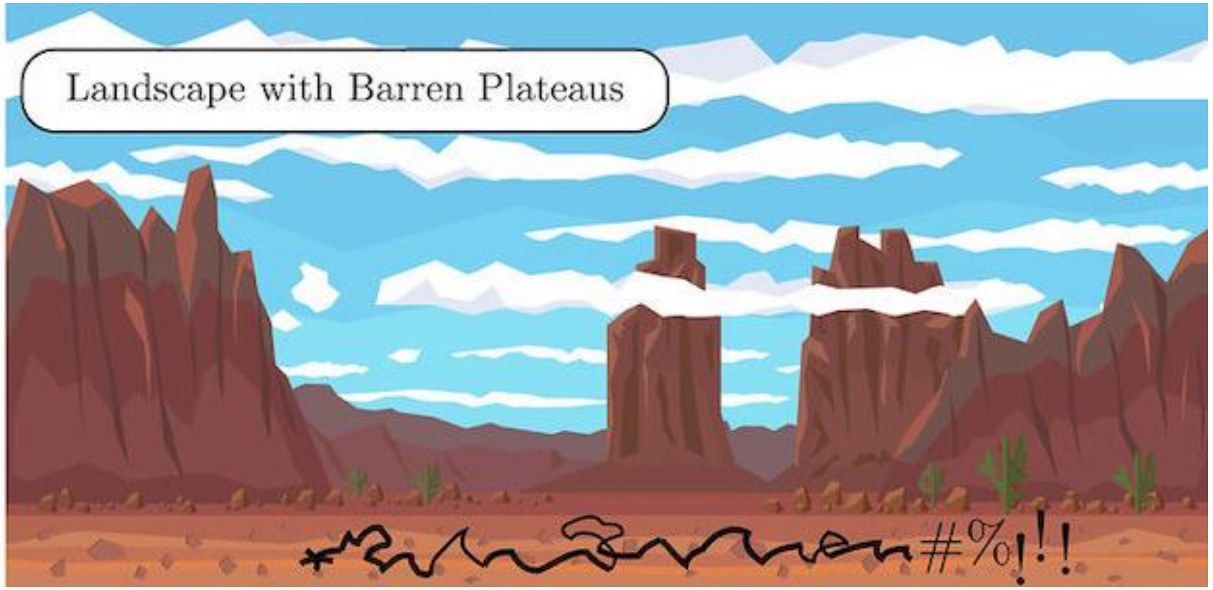
Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum NN

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



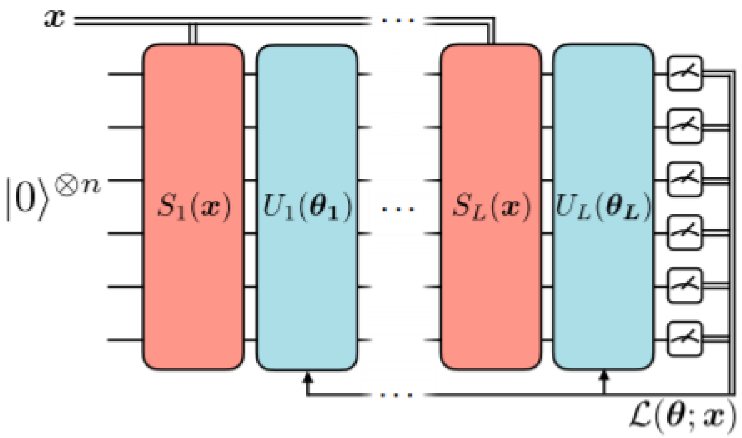
Features that may induce Barren Plateaus

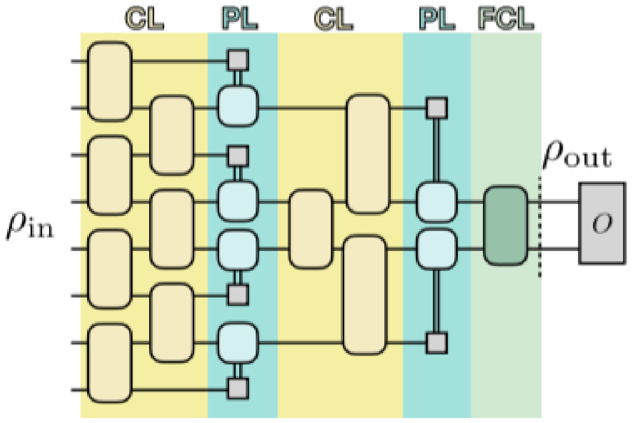


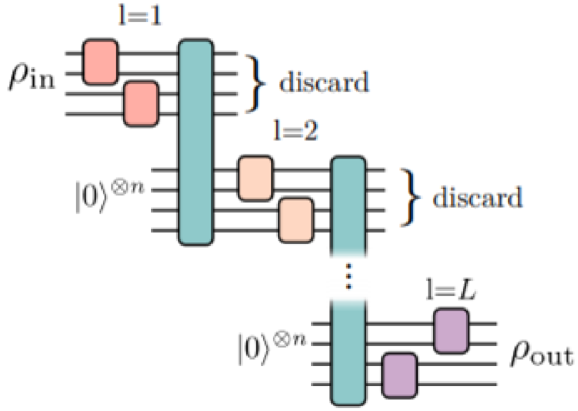
Subtleties in the trainability of QML models: https://arxiv.org/pdf/2110.14753.pdf

Quantum algorithms for NISQ Devices

Quantum Machine Learning (QML) – Quantum NN







Re-Uploding QNN

Universal function approximator

https://arxiv.org/abs/2009.00298

Convolutional QNN

Absence of Barren Plateaus

https://arxiv.org/abs/2011.02966

Dissipative QNN

Backpropagation-like training

https://arxiv.org/abs/1902.10445

Quantum computing models for NN
https://arxiv.org/abs/2102.03879

QUANTUM ADVANTAGE IN THE NISQ ERA?

Quantum algorithms for NISQ Devices

NISQ gate-based hardware resource requirements

resources	initial estimates	realistic estimates and constraints
qubit number	50 qubits for a computational advantage (Preskill)	100s to 1000s qubits for many practical NISQ algorithms to obtain a speedup advantage (Guerreschi, Albino).
computing depth	use shallow algorithms with under 10-gate cycles	most NISQ algorithms in the quantum advantage regime have >100s gate cycles
available fidelities	NISQ is to use currently available qubit fidelities that are in the 99.9% to 99% range	current QPUs either have low fidelities and >30 qubits (transmons) or better fidelities and <30 qubits (trapped ions)
required fidelities	error rate $\ll \frac{1}{\#\, qubits * algo\ depth}$ *for QAOA, but seemingly for other NISQ algorithms as well* *https://iopscience.iop.org/article/10.1088/2058-9565/abae7d* *error rate usually relates to the two-qubit error rate, which should ideally be its minimum error rate and not median/average rate.*	the fidelities requirements are not matched by actual hardware even for the shallowest computing depth 1/(1121 q * 8 d) => **99,99%** possible? 1/(127 q * 8 d) => **99,9%** IBM Heron's 133 qubit QPU in 2024? 1/(65 q * 8 d) => **99,8%** not available. 1/(53 q * 8 d) => **99,7%** Google Sycamore is at 98,6%. *minimum ansatz depth of 8 gate cycles*

https://arxiv.org/ftp/arxiv/papers/2305/2305.09518.pdf

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Quantum Computing Software

Quantum Compting software

PENNYLANE

Qiskit

Cirq

STRAWBERRY FIELDS

aws

Amazon Braket

TensorFlow Quantum

PASQAL

D:WAVE Ocean

Quantum Compting software

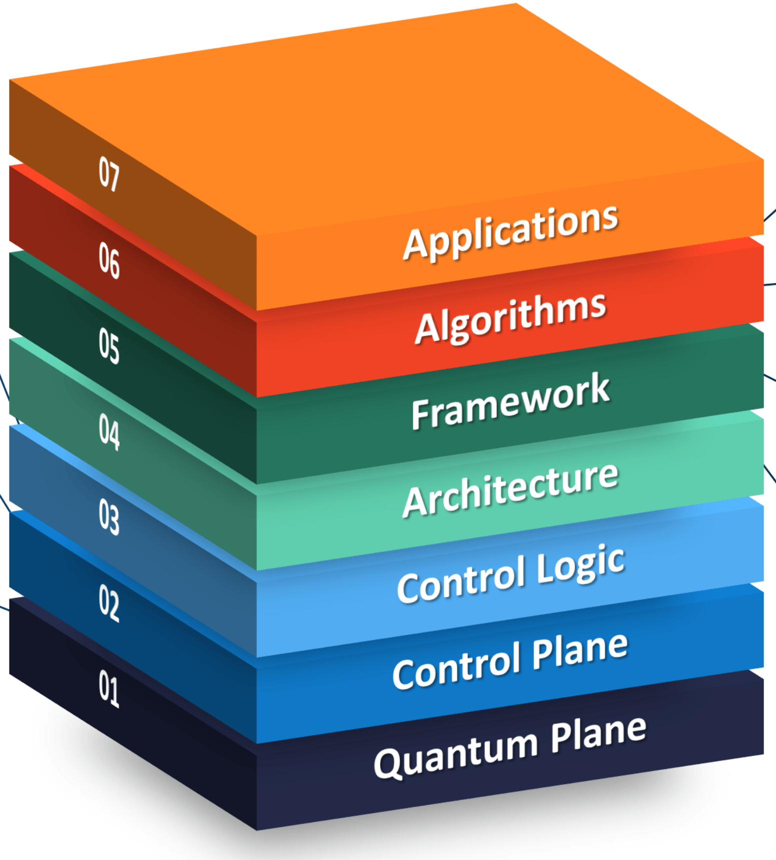
The quantum stack

CONTROL LOGIC
Pulse & timing calibration
Optimal Control
Decoding

CONTROL PLANE
Crosstalk
Wiring/integration
Heat management

QUANTUM PLANE
Fidelity
Native gates
Connectivity
Interconnects

SIMULATOR
Verification & validation
Performance



APPLICATIONS
Development mgt.
Workflow mgt.

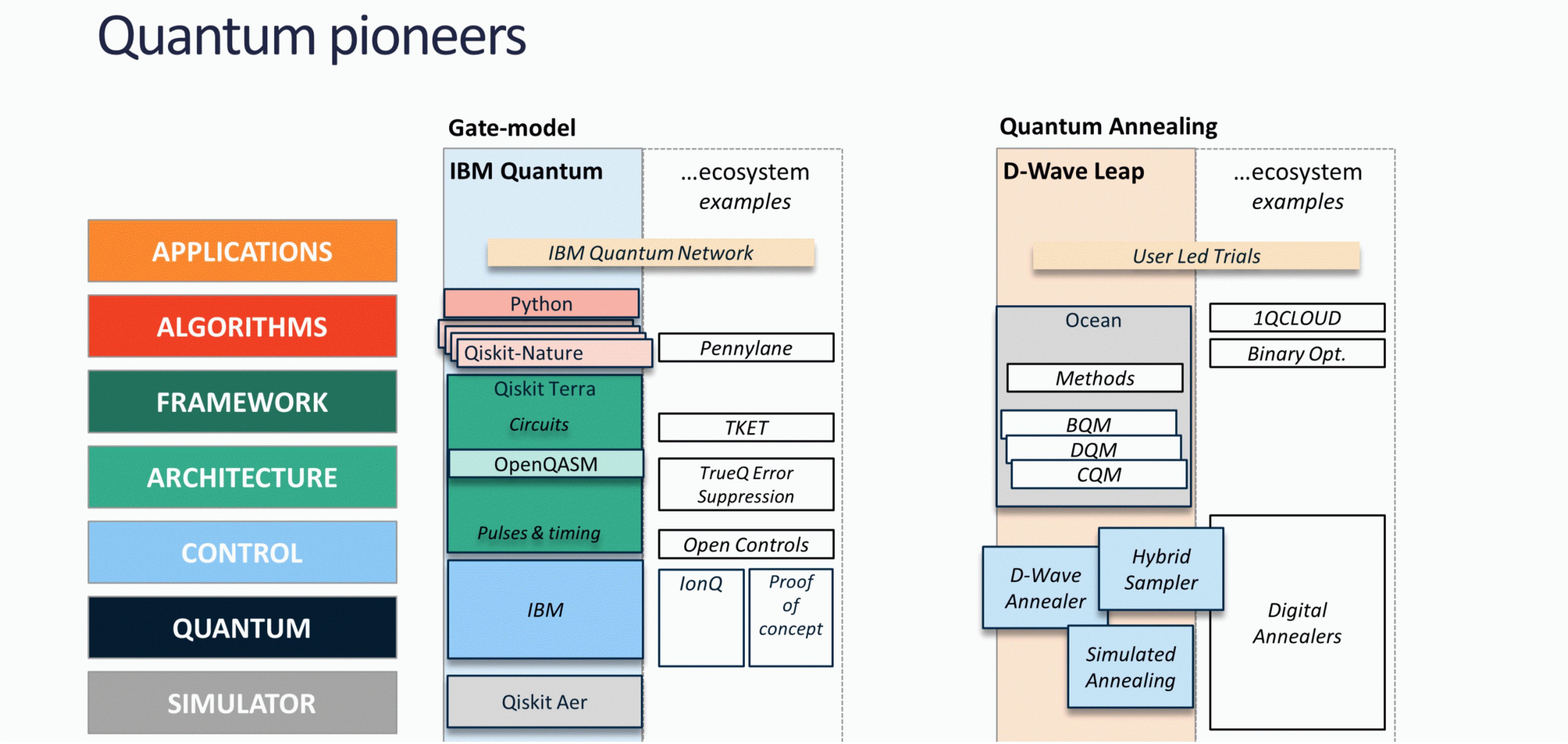
ALGORITHMS
High level languages
Libraries

FRAMEWORK
Circuit model & alternatives
Optimising compilers

ARCHITECTURE
QPU kernel
Quantum error correction
Magic state factories
QRAM

https://quantumcomputingreport.com/

Quantum Compting software



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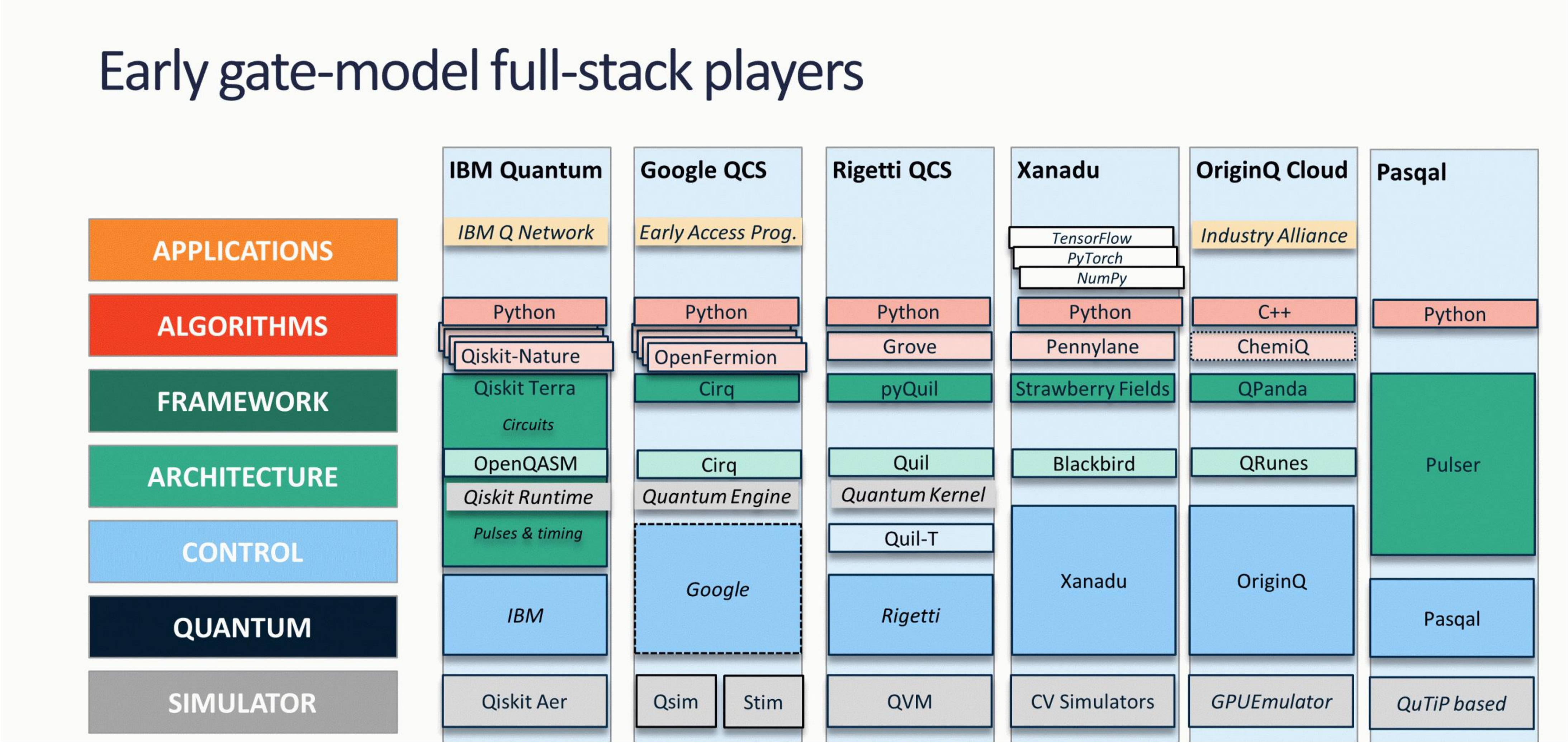
Quantum Compting software



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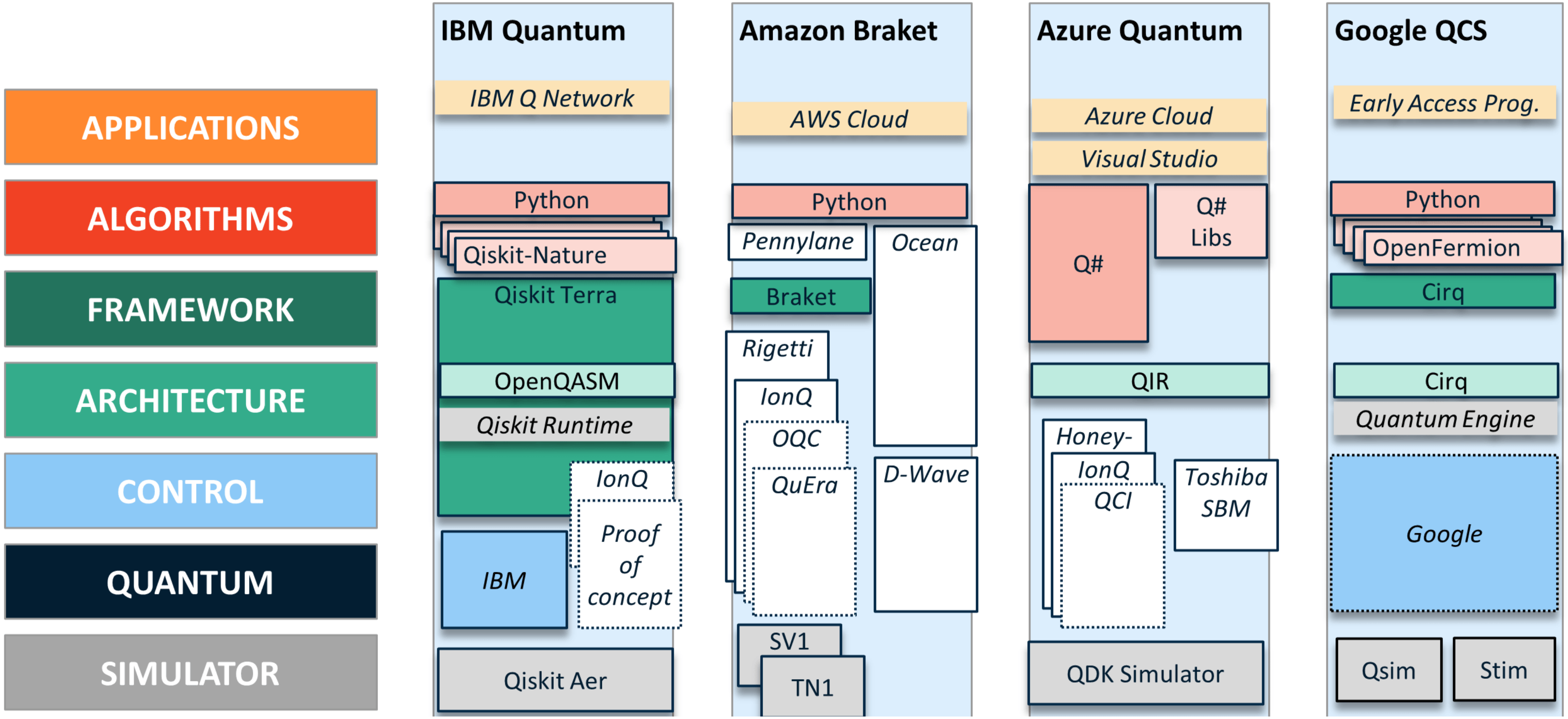
Quantum Compting software

Quantum PaaS (Platform as a Service)



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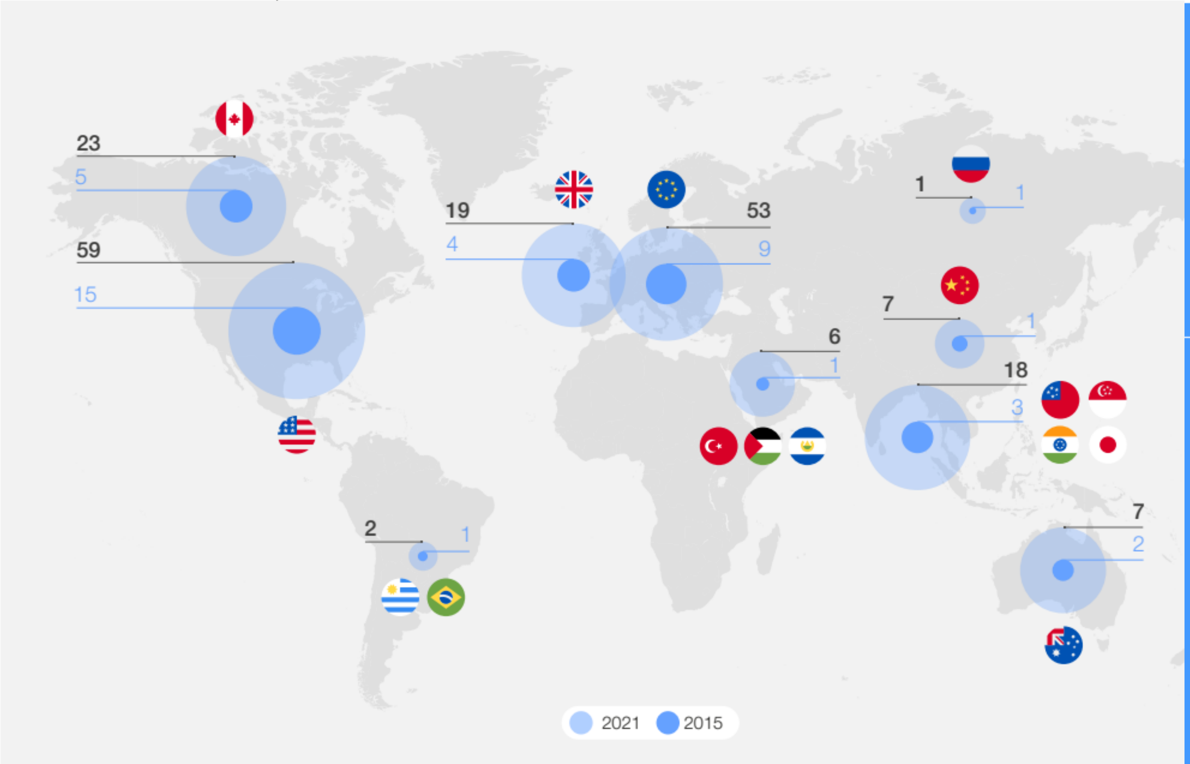
Projects and Fundings

Projects and Fundings

Startup and Private companies

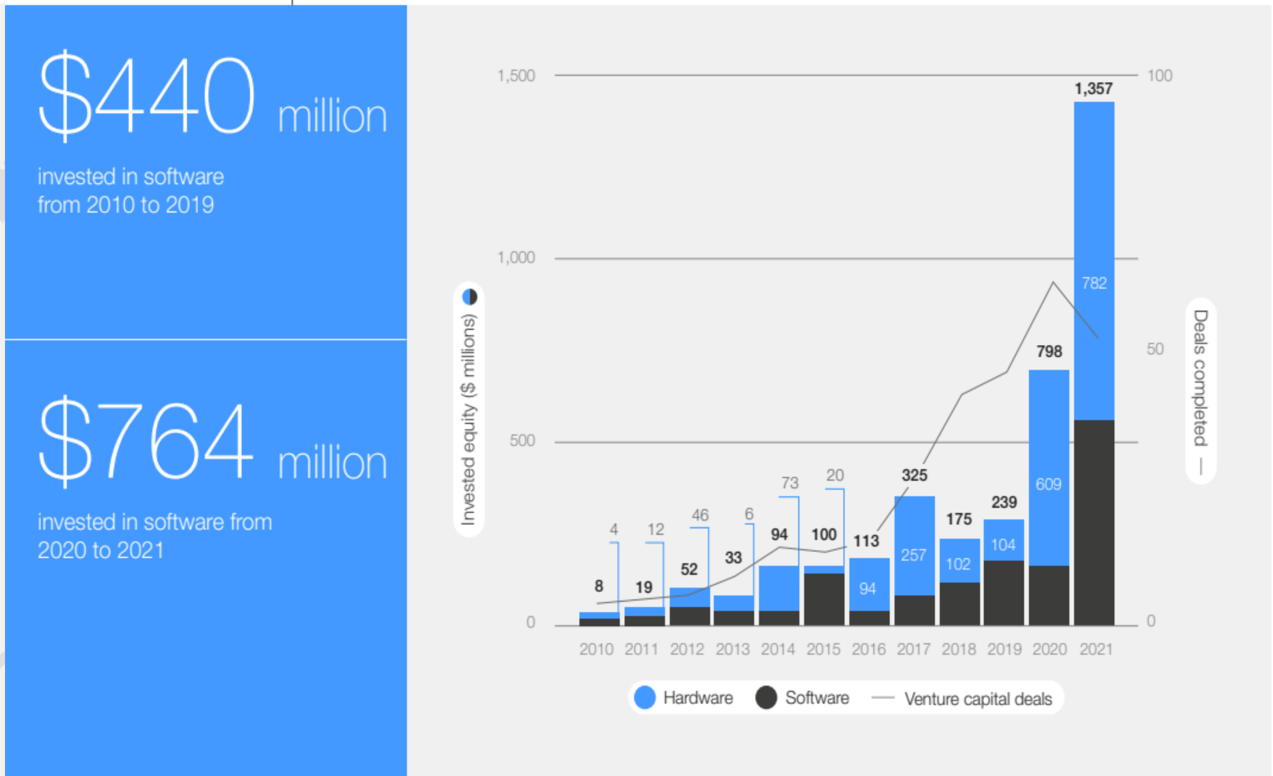
FIGURE 4 | Map of start-ups in quantum computing



Note: Not exhaustive

Source: McKinsey & Company, adapted from PitchBook, 2021, World Economic Forum analysis

FIGURE 7 | As capital investment in quantum computing rises, more money is focused on software



Source: Boston Consulting Group, adapted from PitchBook, 2021

State of Quantum Computing: Building a Quantum Economy 14

https://www3.weforum.org/docs/WEF_State_of_Quantum_Computing_2022.pdf

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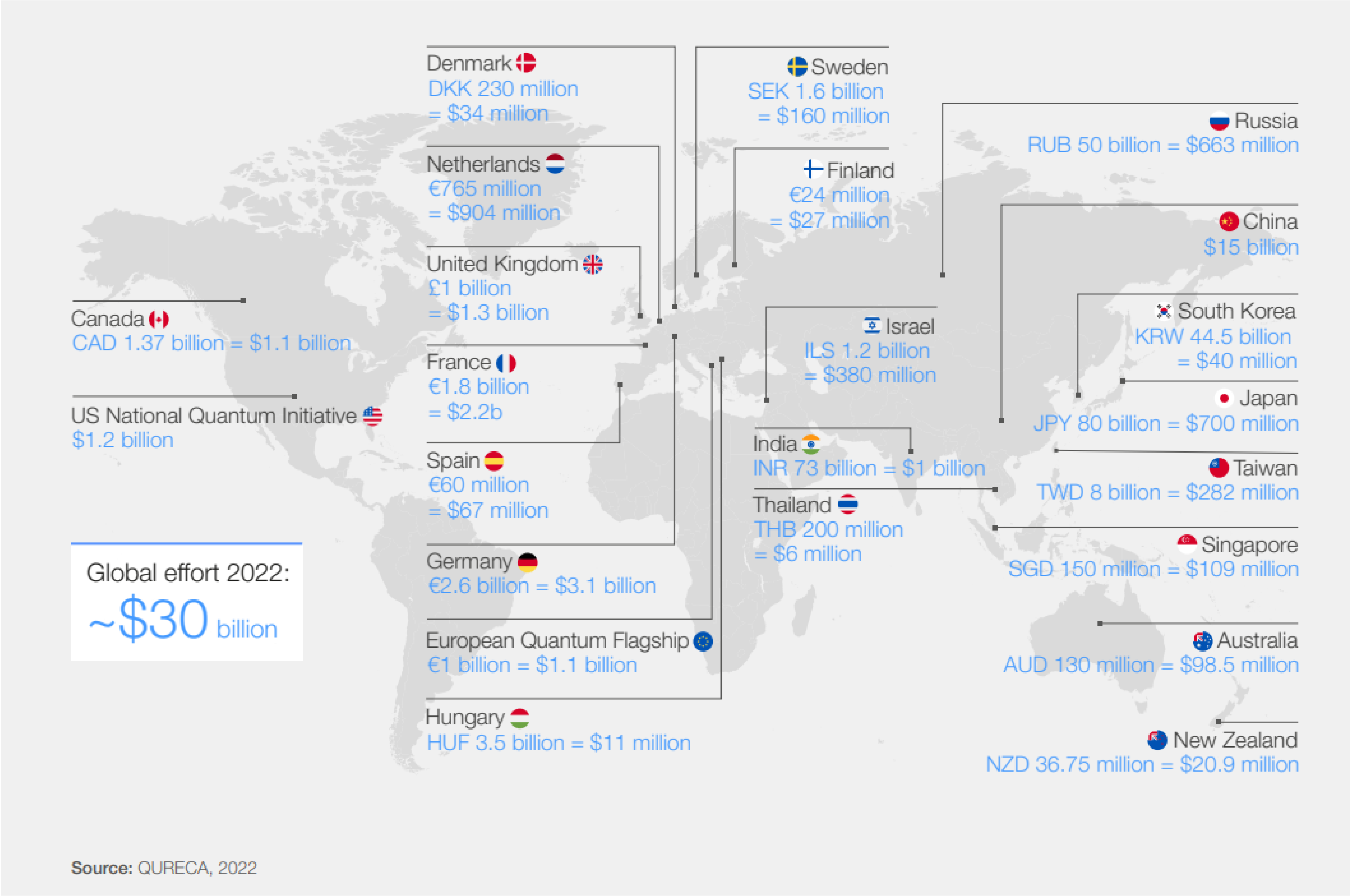
Projects and Fundings

Public investments



Map of global public investments in quantum technologies

Global effort: 30 Billion dollars

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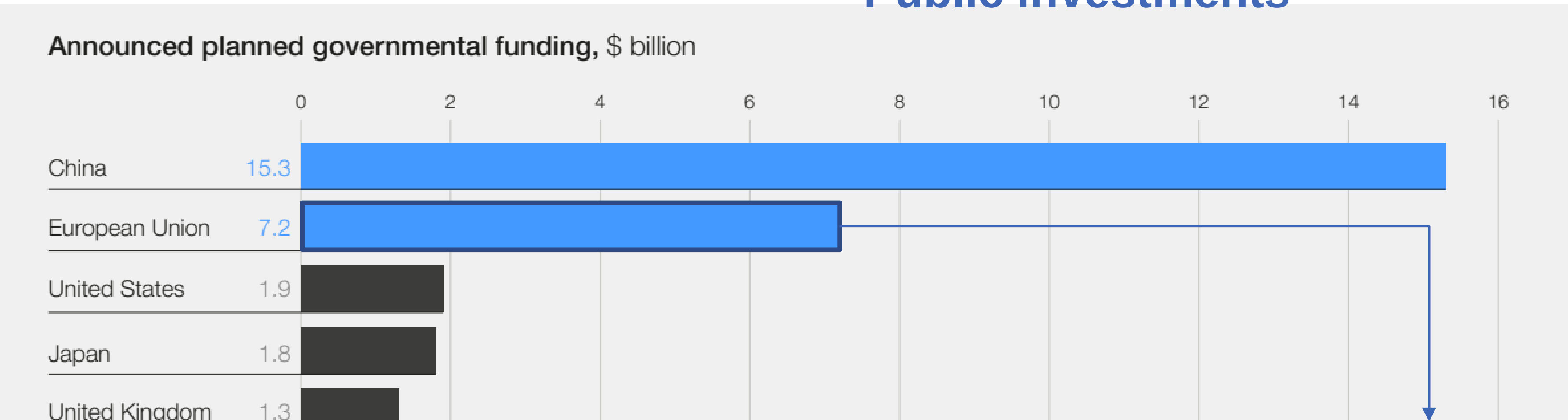
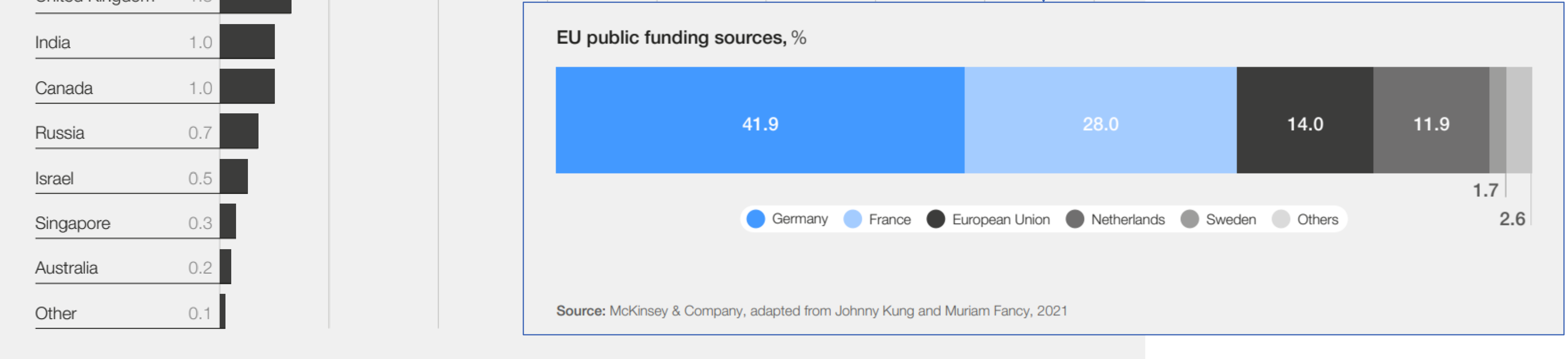
Projects and Fundings

Public investments





https://www3.weforum.org/docs/WEF_State_of_Quantum_Computing_2022.pdf

Projects and Fundings

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

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

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

- The **European Processor Initiative (EPI)** is a project whose aim is to design and implement a roadmap for a new family of low-power European processors for extreme scale computing, high performance Big-Data and a range of emerging applications.

Projects and Fundings

The **HPCQS** consortium was born with the idea of combining HPC and QC hardware and software.

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

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

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

⟨HPC|QS⟩

ParTec Modular Supercomputing · cnrs · parityqc · FLYSIGHT · Atos

JÜLICH Forschungszentrum · cea · GENCI · ICHEC Irish Centre for High-end Computing

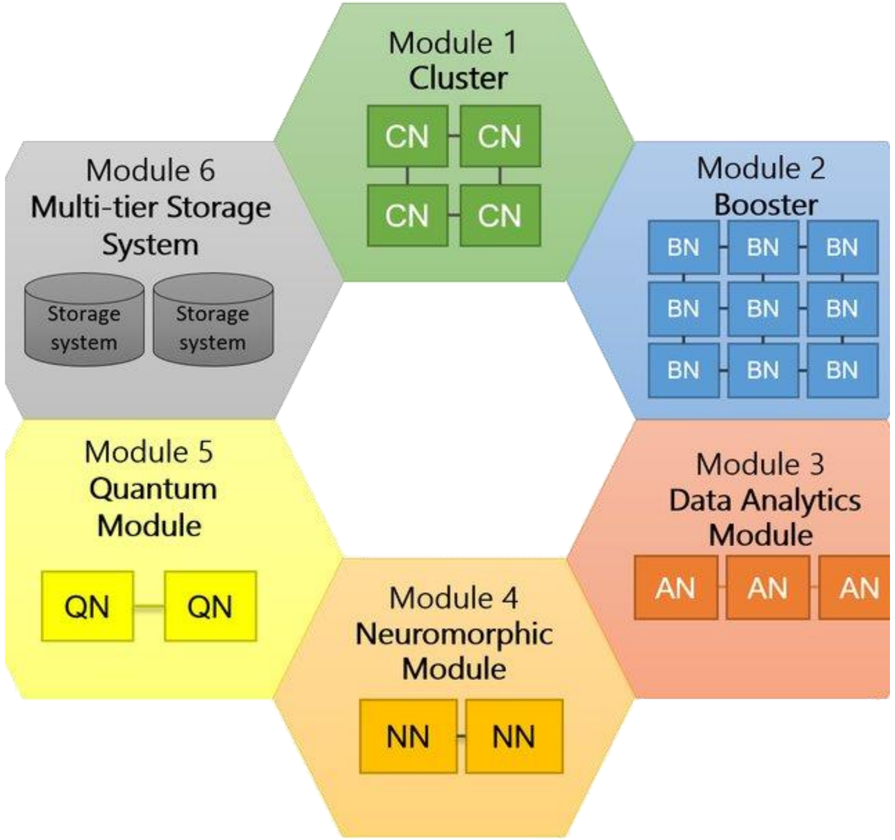
SORBONNE UNIVERSITÉ · CentraleSupélec · CINECA · universität innsbruck

Inria · BSC Barcelona Supercomputing Center Centro Nacional de Supercomputación · EURICE European Research and Project Office GmbH · Fraunhofer

https://www.hpcqs.eu/

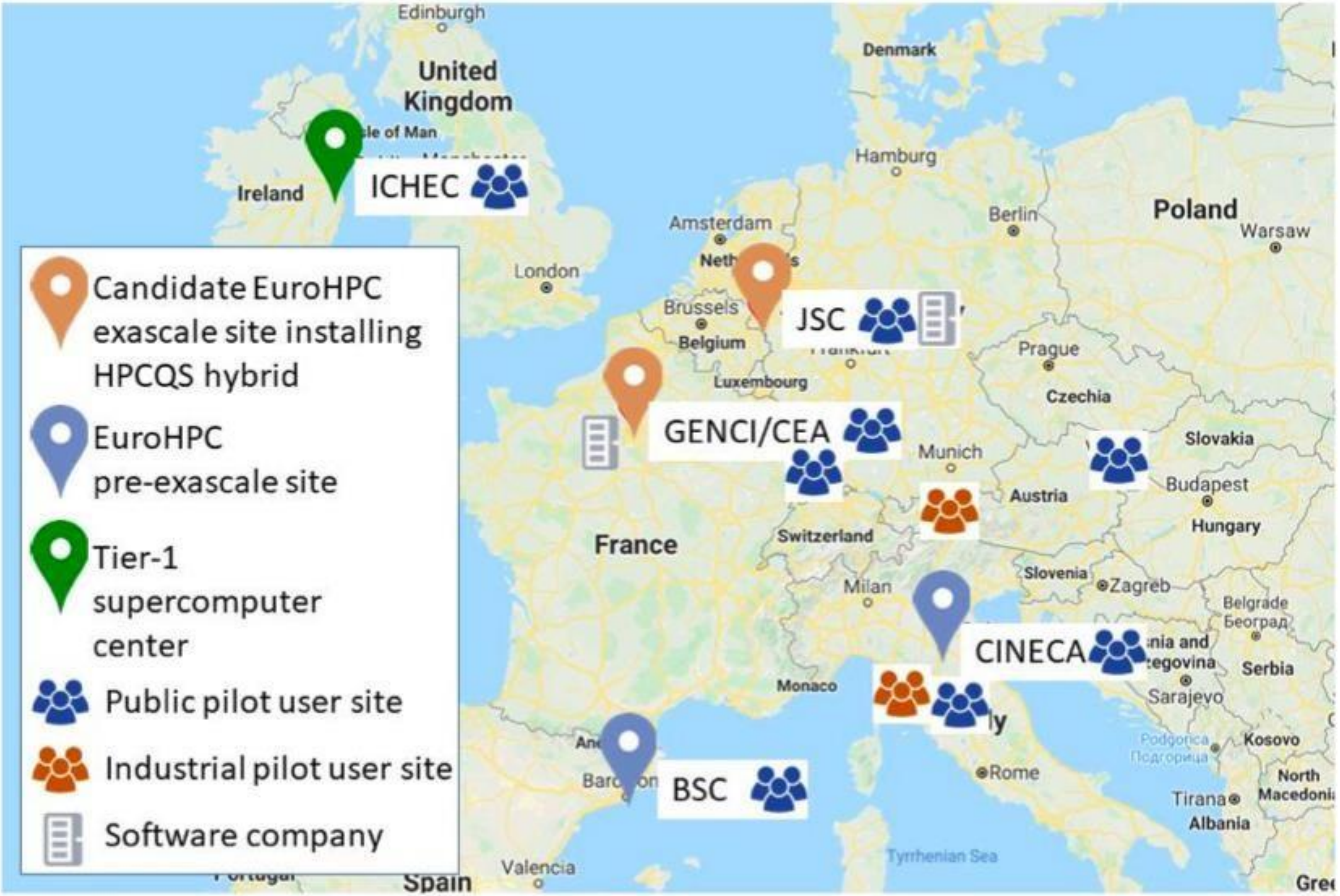
Modular Supercomputer Architecture

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



HPCQS

Projects and Fundings



FZJ (Coordinator)	CNRS
ParTec (LTP*[1])	Sorbonne (LTP*)
CEA	SUPELEC (LTP*)
GENCI	INRIA
ATOS	Pasqal
CNR	CINECA
NUIG-ICHEC	BSC
	FLS
UIBK	Parity QC
EURICE	Fraunhofer IAF

Projects and Fundings: ITALY

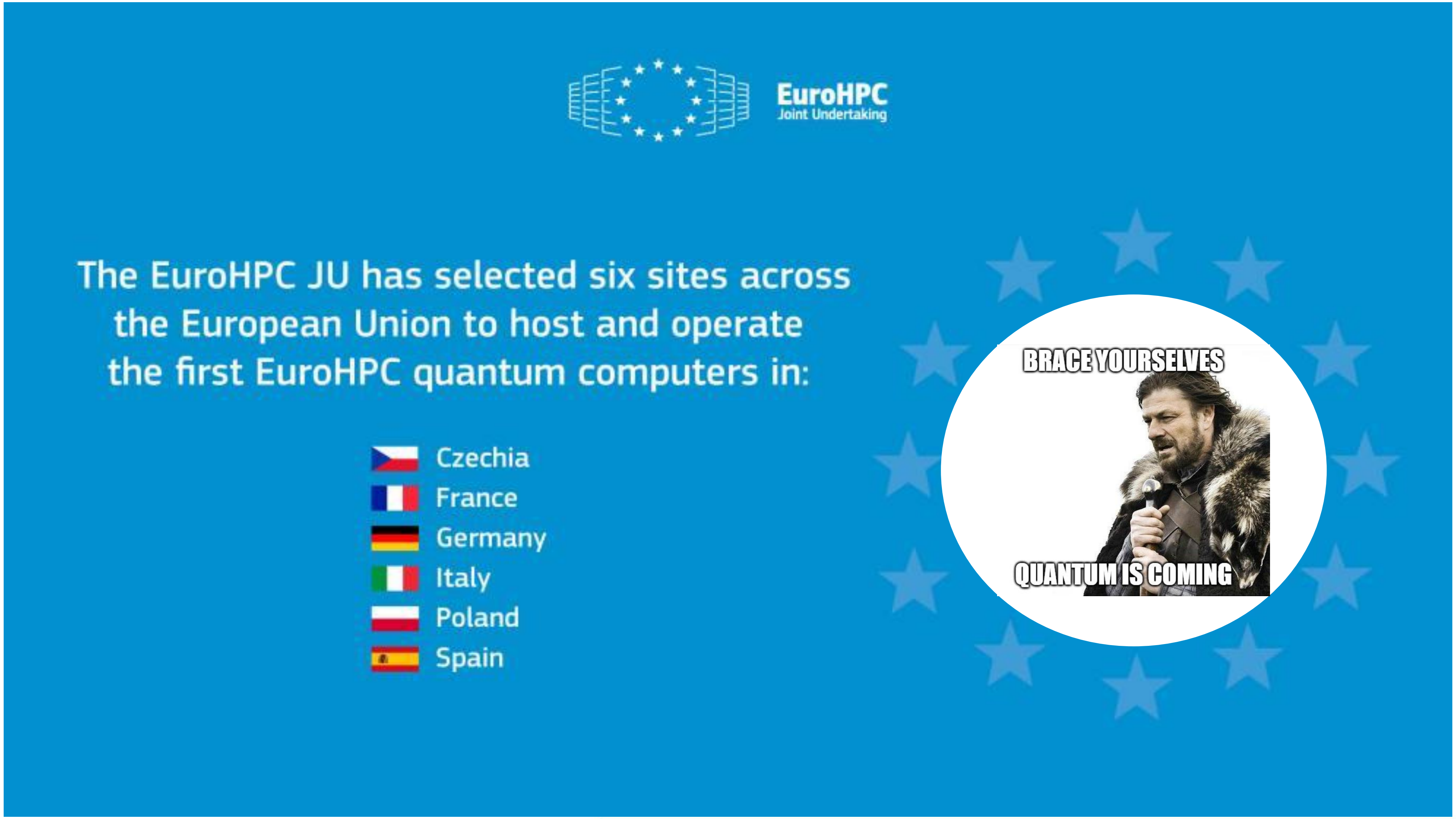
- **ISCRA-C**: Quantum Computing as a Service

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

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

https://www.hpc.cineca.it/services/iscra

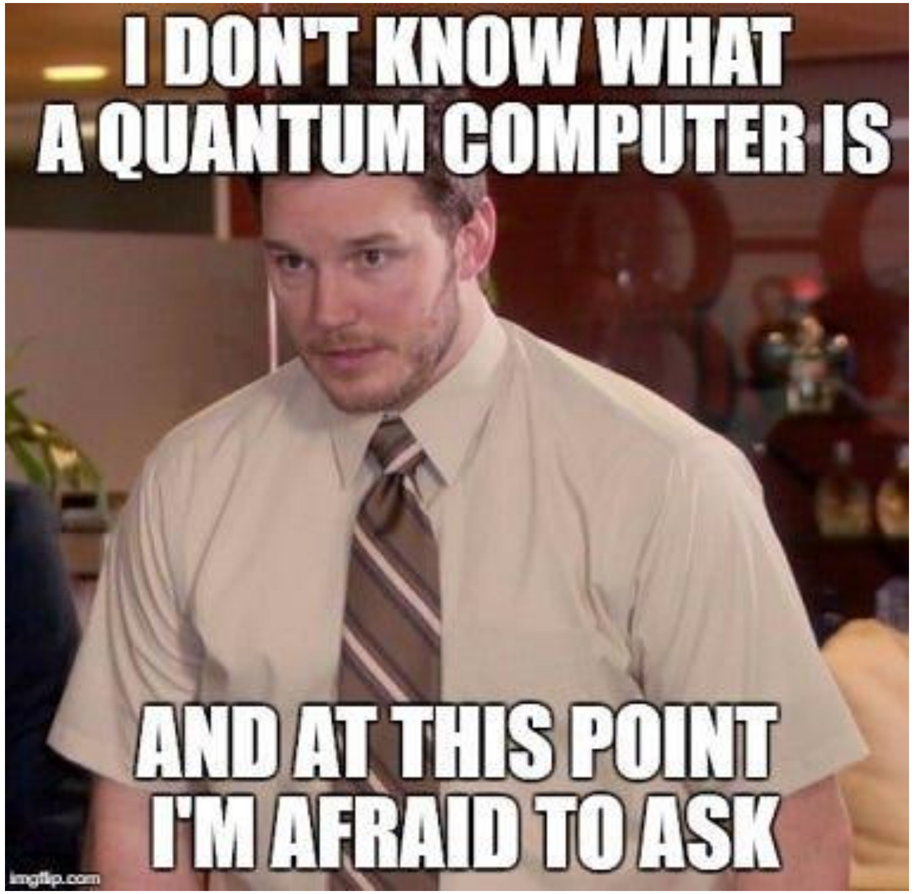
Projects and Fundings



https://eurohpc-ju.europa.eu/selection-six-sites-host-first-european-quantum-computers-2022-10-04_en

Thanks

I hope you don't feel like this..



Quantum Computing @ CINECA

CINECA: Italian HPC center

CINECA Quantum Computing Lab:

- Support research Universities, Industries and QC startups

- Internship programs, Courses and Conference (HPCQC)

https://www.quantumcomputinglab.cineca.it

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