From Classical to <Quantum|Computing>

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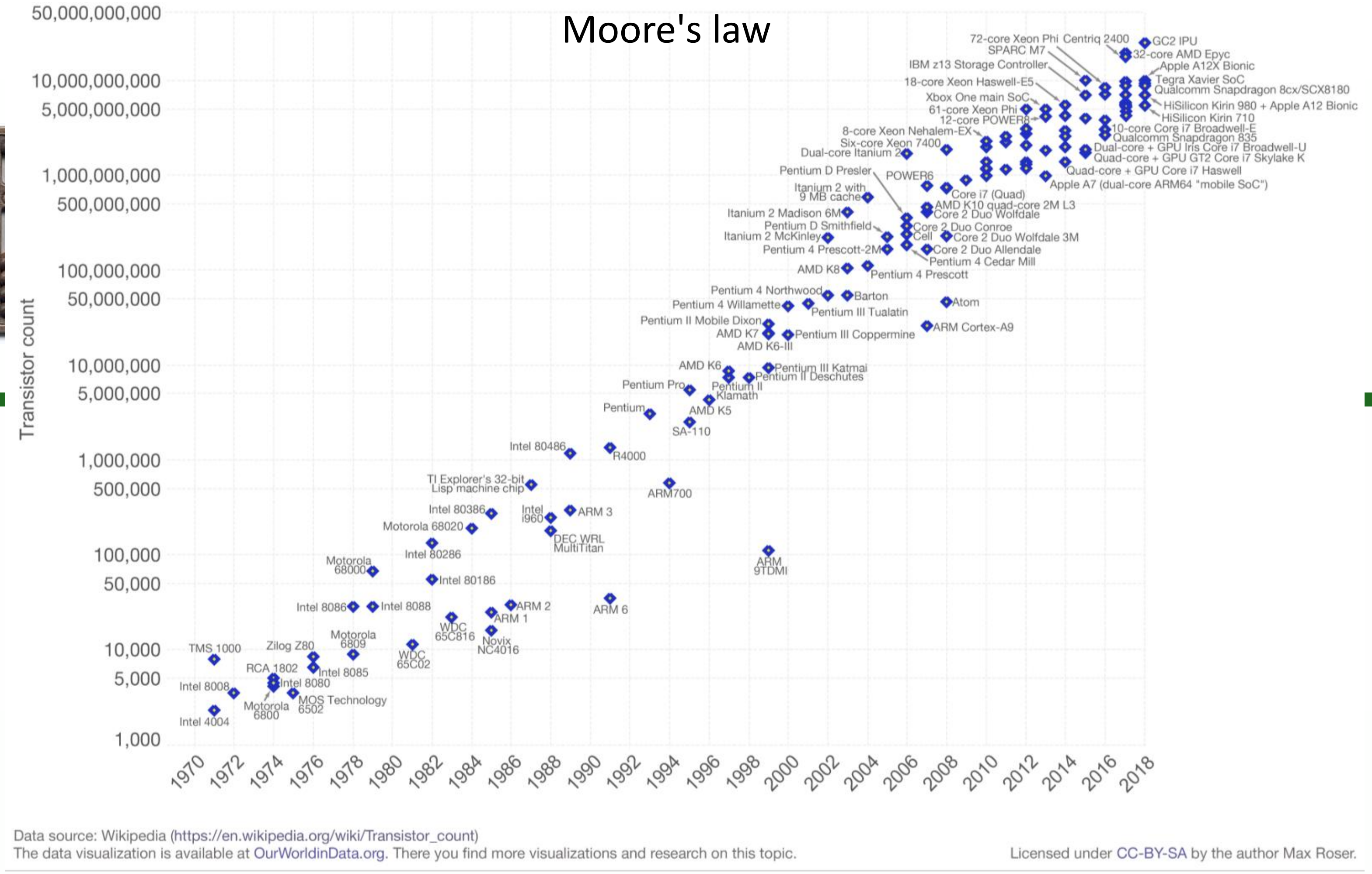
History of computing



Can we think of another computing paradigm?

Simulating Physics with Computers - 1982

“The first question is, What kind of computer are we going to use to simulate physics? ….

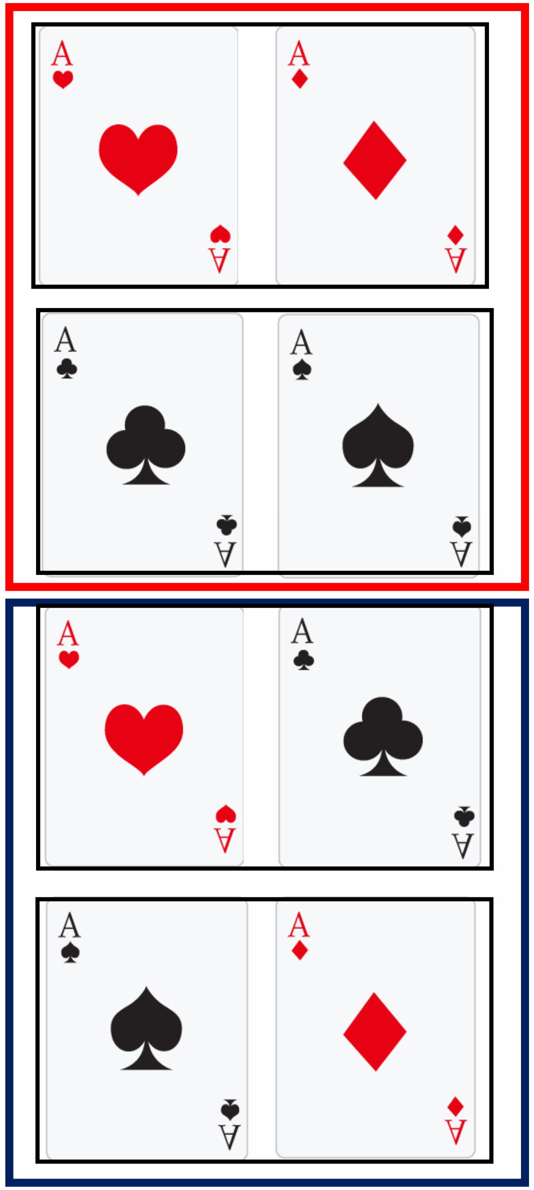
Can physics be simulated by a universal computer? “

Quantum Computing

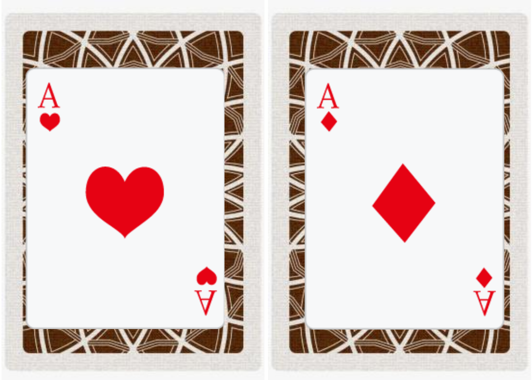
What can it do?

Constant

Balanced



How many draws?



Deutsch-Jozsa algorithm - 1985

Classically, we need

$\sim 2^{n-1}$

In general

Using quantum computing

1

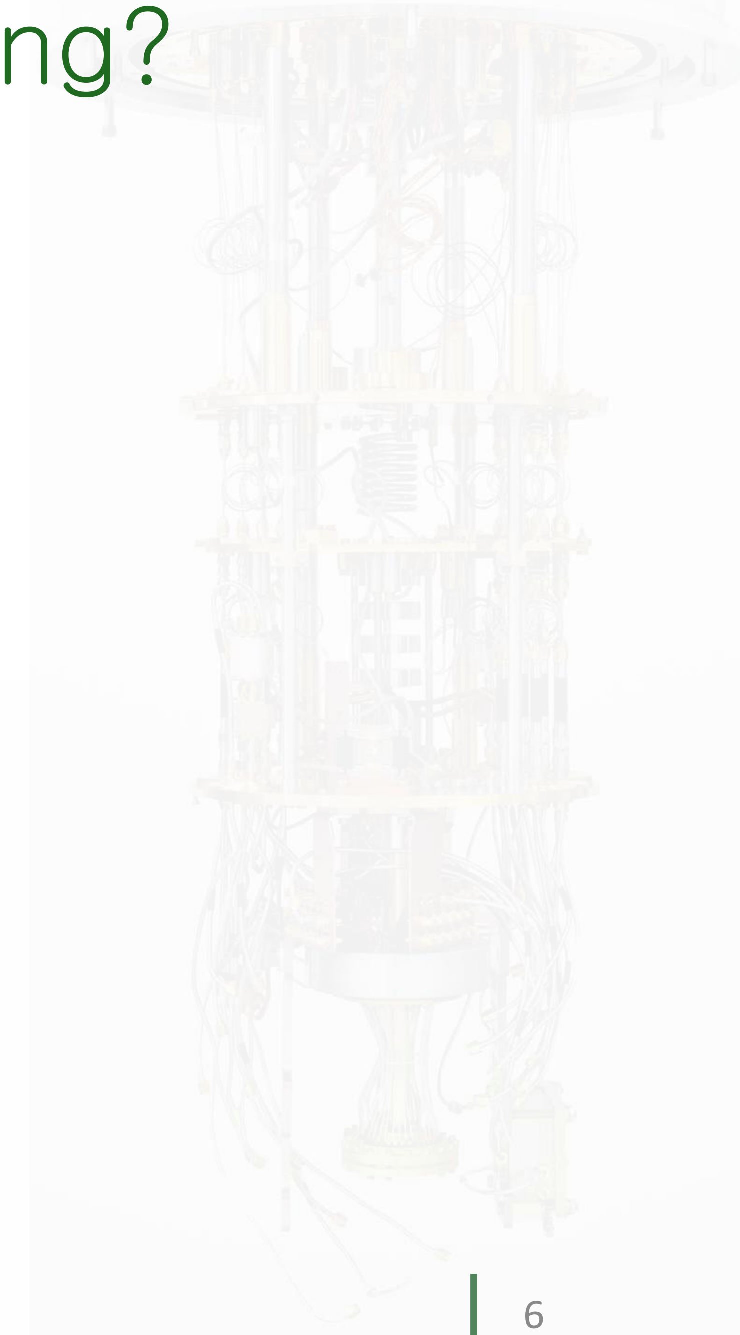
Quantum Computer Architectures

Quantum annealers

Google Quantum AI

Gate-based quantum computers

What is quantum computing?



Four postulates

First postulate

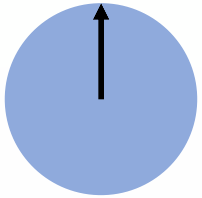
Superposition

Bit

0

1

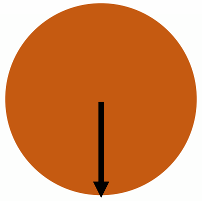
0



1

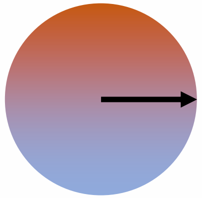
$|0\rangle$

0



1

$|1\rangle$

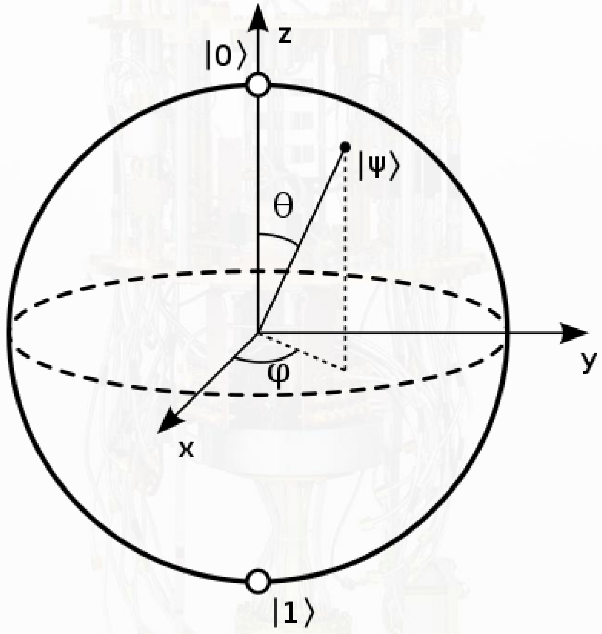


$|0\rangle$ $|1\rangle$

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

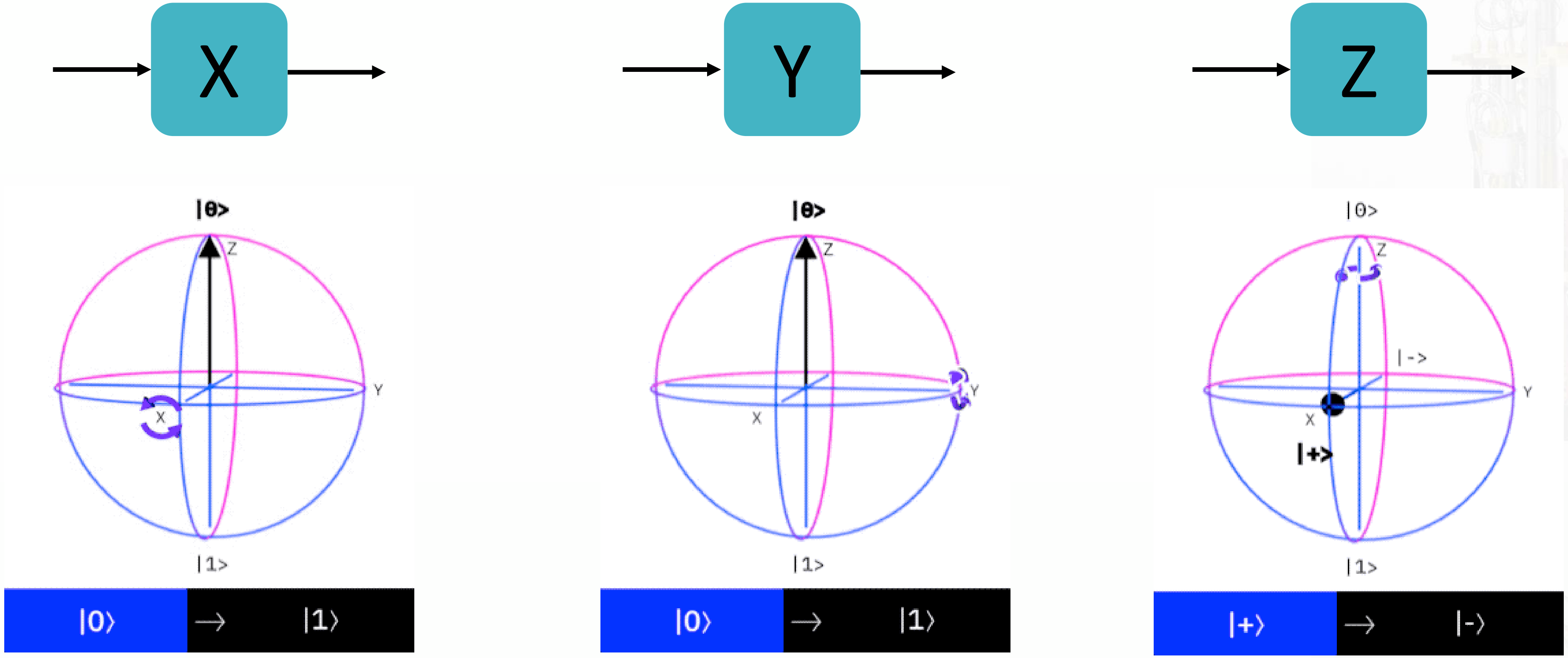
$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Block sphere



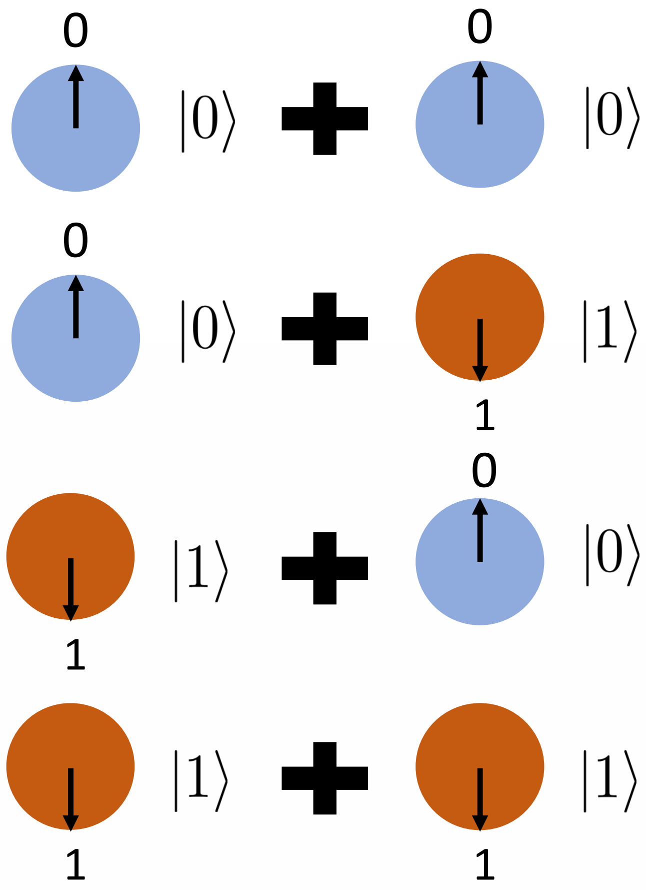
Second postulate

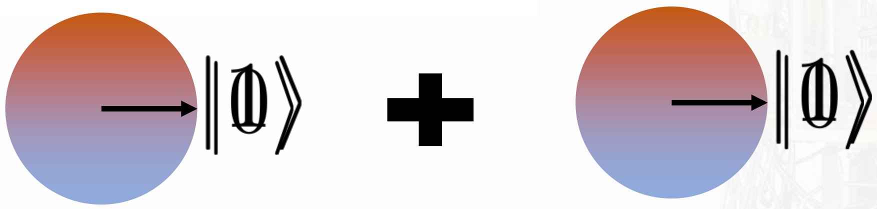
Qubit Evolution



Quantum parallelism

We can “ADD” two qubits

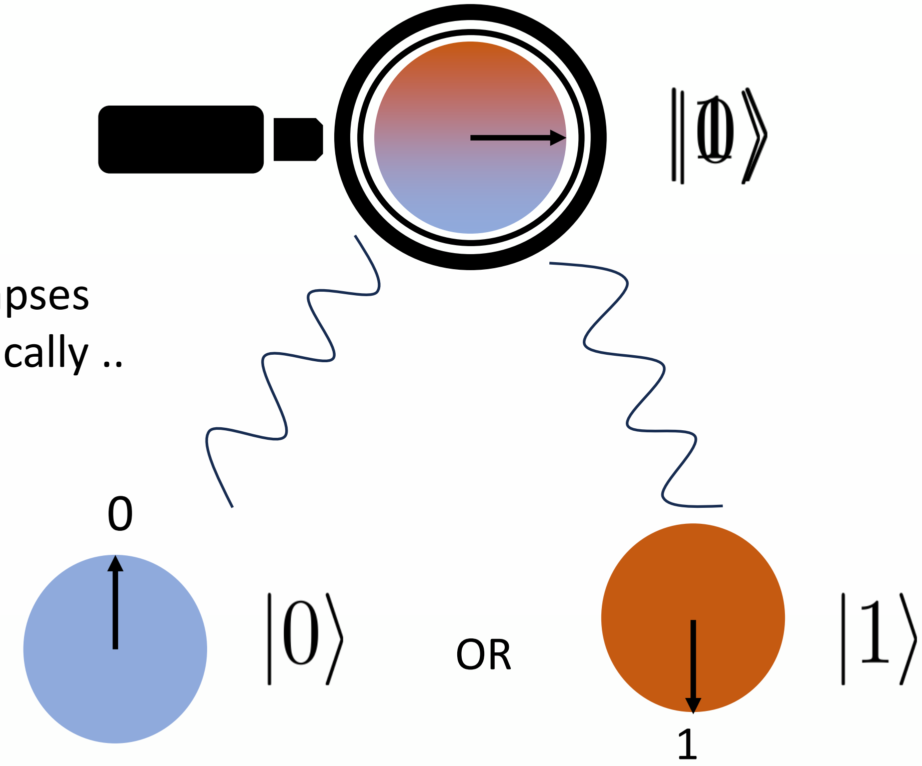




Third postulate

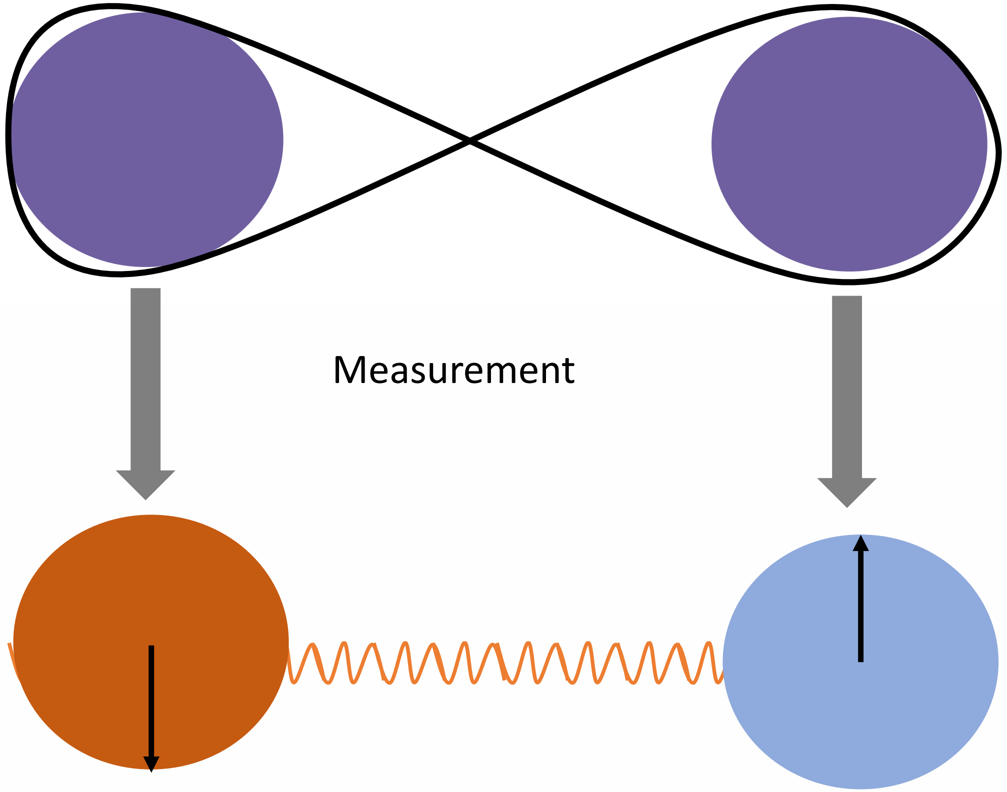
Measurement

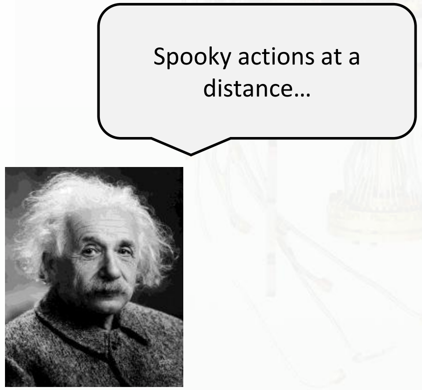
States collapses
probabilistically ..



Fourth postulate

Entanglement





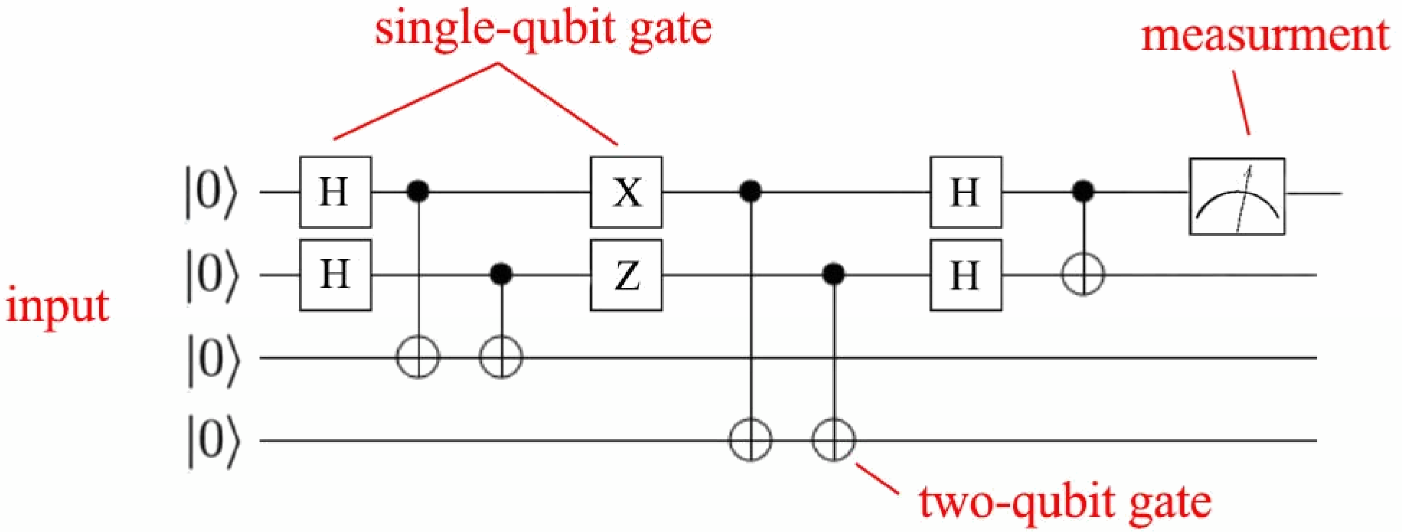
Full-fledged quantum computers

A quantum computer consists of multiple qubits

$$|\psi_0\psi_1\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle \qquad \alpha, \beta, \gamma, \delta \in \boldsymbol{C}$$

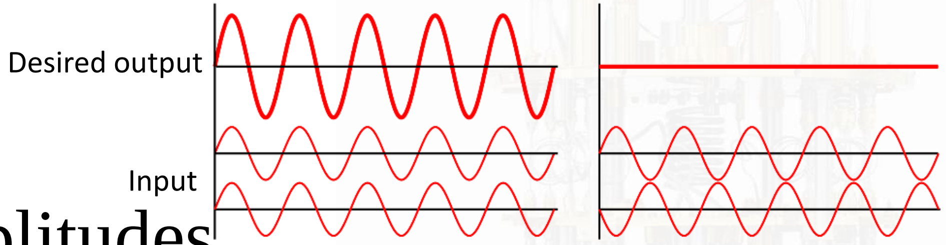
$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$$

Can apply quantum gates to a subset of qubits in a multi-qubit state



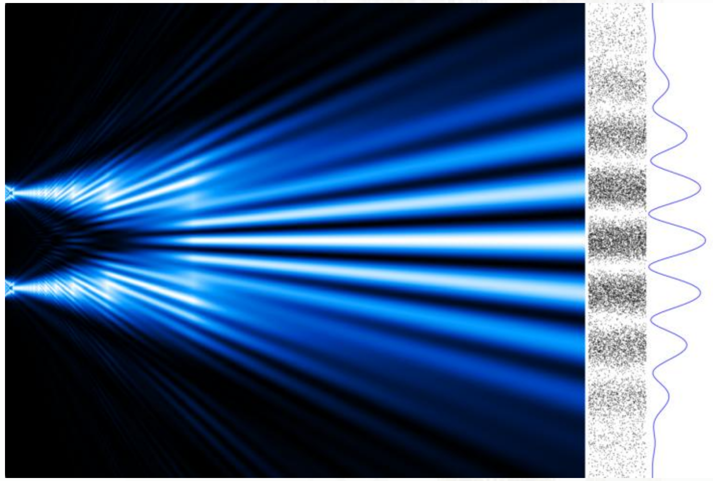
Secret sauce of quantum algorithms

- **Warning:** a quantum computer does *not* simply "try out all solutions in parallel"



- The magic comes from allowing complex (or even just negative real) superposition amplitudes

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |+\beta|^2 = 1$$



- Can *carefully* choreograph computations so that wrong answers "cancel" out their amplitudes, while correct answers "combine" to produce the desired output (**quantum interference**)

Shor’s algorithm – 1994

Problem: Given a large integer N (typically several hundred digits long), factorize N as a product of primes.

Steps :

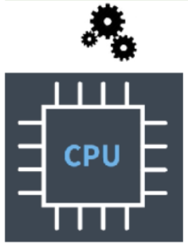
1. Pick a random number a < N.
2. Compute gcd(a,n).
3. If gcd(a, N) ≠ 1,then it is a non-trivial factor of N, then we are done.
4. Otherwise, use the period-finding subroutine (below) to find r, the period of the following function:

$$f(x) = a^x \bmod N$$

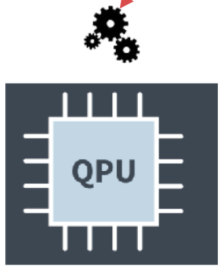
5. If r is odd, go back to step 1.
6. If $a^{r/2} = -1 \pmod N$, go back to step 1.

Quantum Part

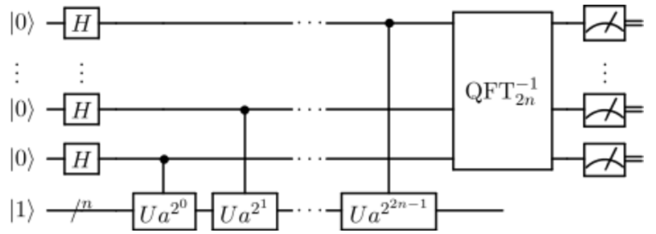
Classical Part



Classical Processor

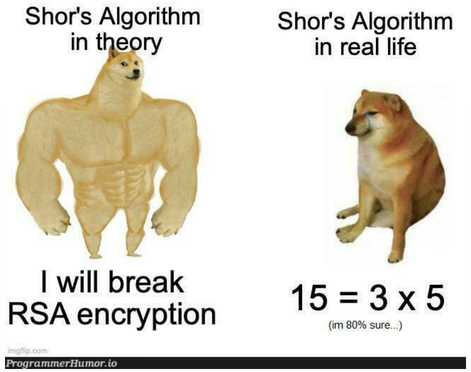


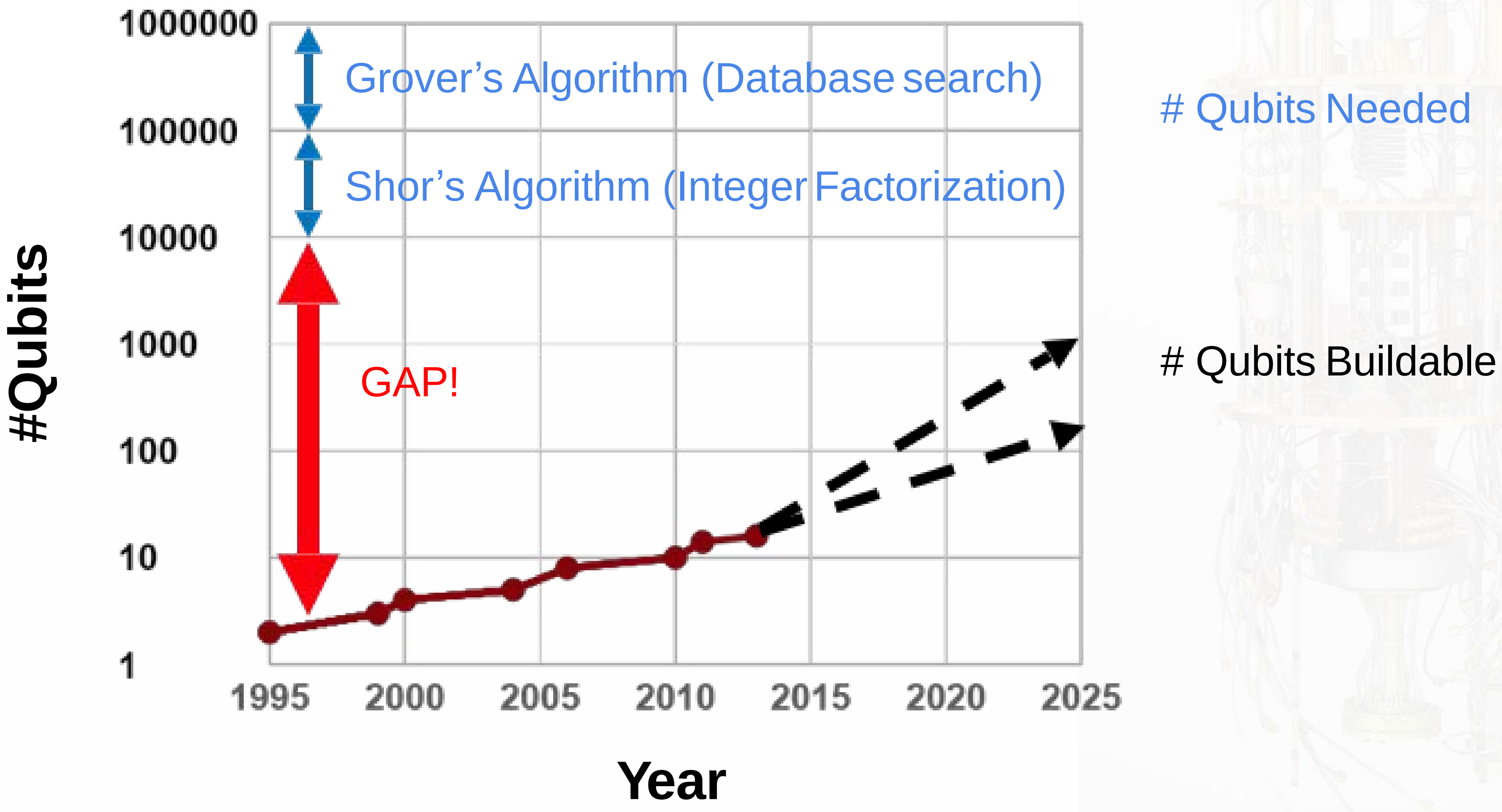
Quantum Processor



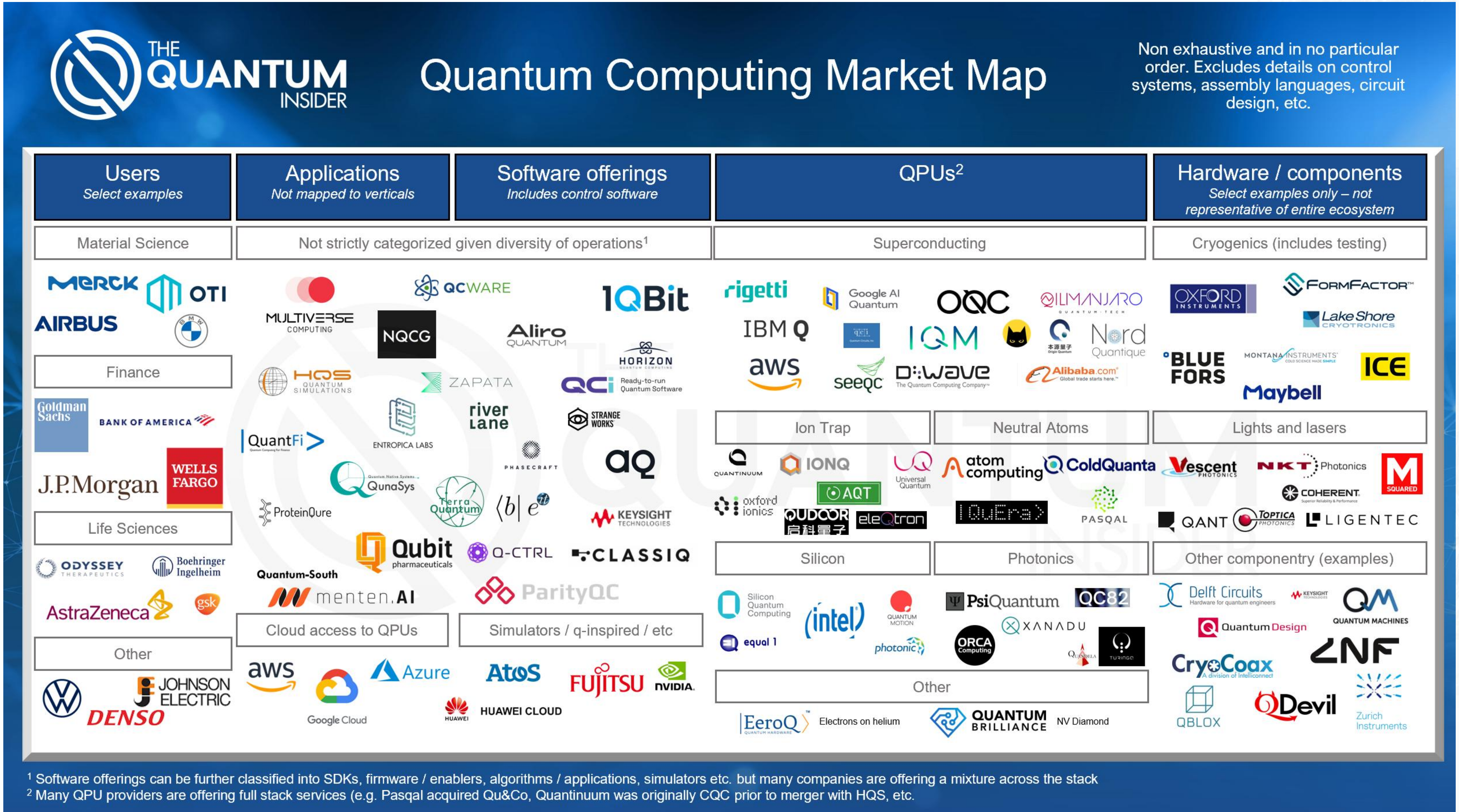
Quantum Subroutine in Shor's algorithm.

The algorithms to machines gap



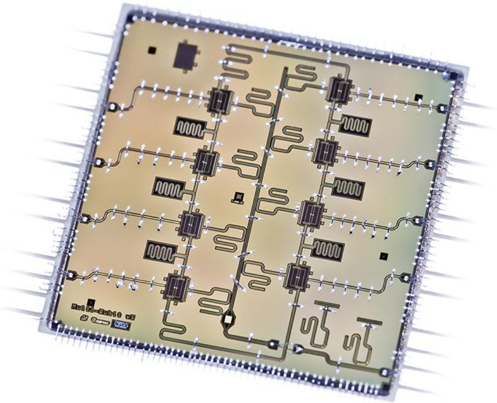


Quantum computing landscape

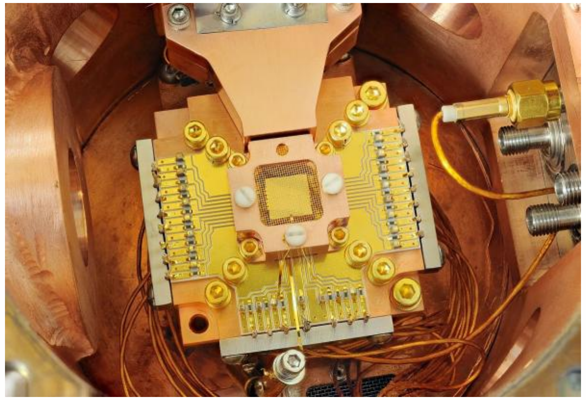


Quantum hardware

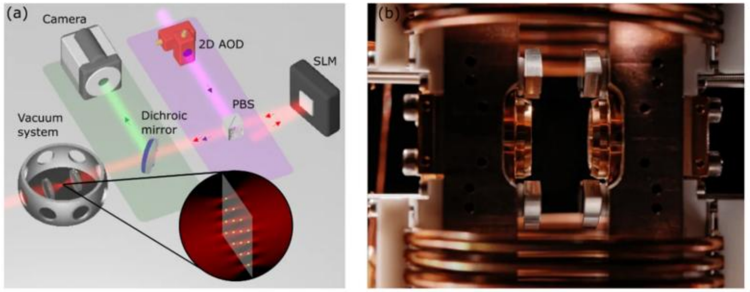
Superconducting qubits



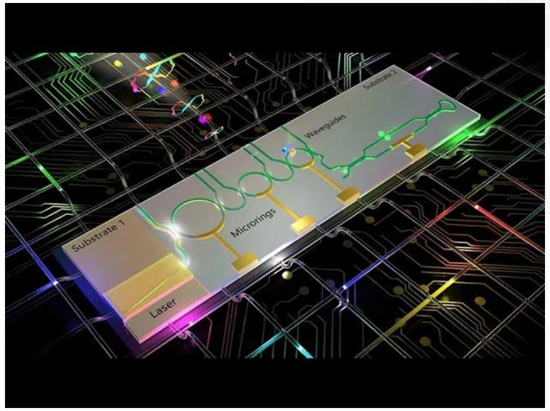
Trapped ions



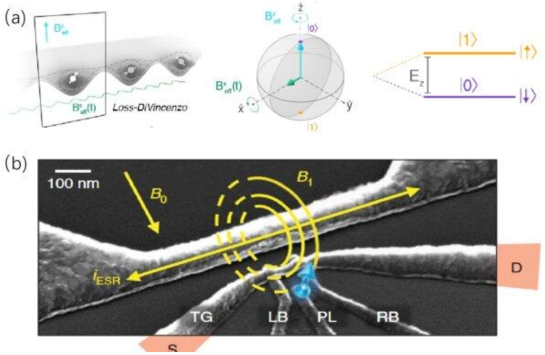
Neutral atoms



Photonic qubits



Spin qubits



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 (2024)
- Functions (2025)
- Mapping Collection (2026)
- Specific Libraries (2027–2029)
- General purpose QC libraries (2033+)

Researchers

Middleware

- Quantum Serverless (2023)
- Transpiler Service (2024)
- Resource Management (2025)
- Circuit Knitting x P (2026)
- Intelligent Orchestration (2027–2029)
- Circuit libraries (2033+)

Quantum Physicist

Qiskit Runtime

- IBM Quantum Experience (2016–2020)
- QASM3 (2021)
- Dynamic circuits (2022)
- Execution Modes (2023)

Early	Canary 5 qubits; Albatross 16 qubits; Penguin 20 qubits; Prototype 53 qubits
Falcon	Benchmarking 27 qubits
Eagle	Benchmarking 127 qubits
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

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
- Heron: Architecture based on tunable-couplers
- Flamingo: Demonstrate scaling with modular connectors
- Crossbill: m- coupler
- 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

Executed by IBM

On target

Public Roadmap

PASQAL

Technology
PASQAL & affiliated ecosystem

Products

	2022 - 2023	2024 - 2025	2026 - 2027	2028+
HARDWARE PLATFORM				
Max qubits	200	1,000	10,000	
Addressability	Z add	Z+X add; Addressable 1Q and 2Q gates		
Base repetition rate	1 Hz	3 Hz	10 Hz	100 Hz
FTQC Program		Atom shuttling; Ultra High-Fidelity Gates	Scalable logical qubits architecture	
HARDWARE ACCELERATED LIBRARIES				
Quantum Matter & Quantum AI	Algorithm Blueprint	Algorithm Development	Production	
QUANTUM PROCESSORS				
Generation	**Orion Alpha** ~3M gates	**Orion Beta** ~5M gates On premise delivery; **Orion Gamma** ~10M gates On premise delivery	**Vela** ~40M gates; **Pegasus** ~200M gates	**Centaurus** **FTQC QPU** 128+ Logical qubits 200M+ gates
Total hours of QPU for users	500	5-10,000; 20-30,000	60-70,000; 200-250,000	500-550,000
Factories	France	Canada; Factory 3		
COMMUNITY				
Platform		Learn; Interact	Collaborate	
Open-source Software Stack	Pulser	Qadence; Solvers & Emulators		

Development roadmap

QUANTINUUM

	2020	2023	2025	2027	2029
SYSTEMS:	SYSTEM MODEL H1	SYSTEM MODEL H2	QUANTINUUM HELIOS	QUANTINUUM SOL	QUANTINUUM APOLLO
PHYSICAL QUBITS:	20	56	96	192	1000's
PHYSICAL 2-QUBIT GATE ERROR:	1×10^{-3}	1×10^{-3}	$< 5 \times 10^{-4}$	$< 2 \times 10^{-4}$	1×10^{-4}
LOGICAL QUBITS:		10+	~ 50	~ 100	100's
LOGICAL ERROR RATES:		1×10^{-3}	$< 10^{-4}$	$\sim 10^{-5}$	1×10^{-5} to 1×10^{-10}*

*analysis based on recent literature in new, novel error correcting codes predict that error could be as low as 1E-10 in Apollo (ref: arXiv:2403.16054, arXiv:2308.07915)

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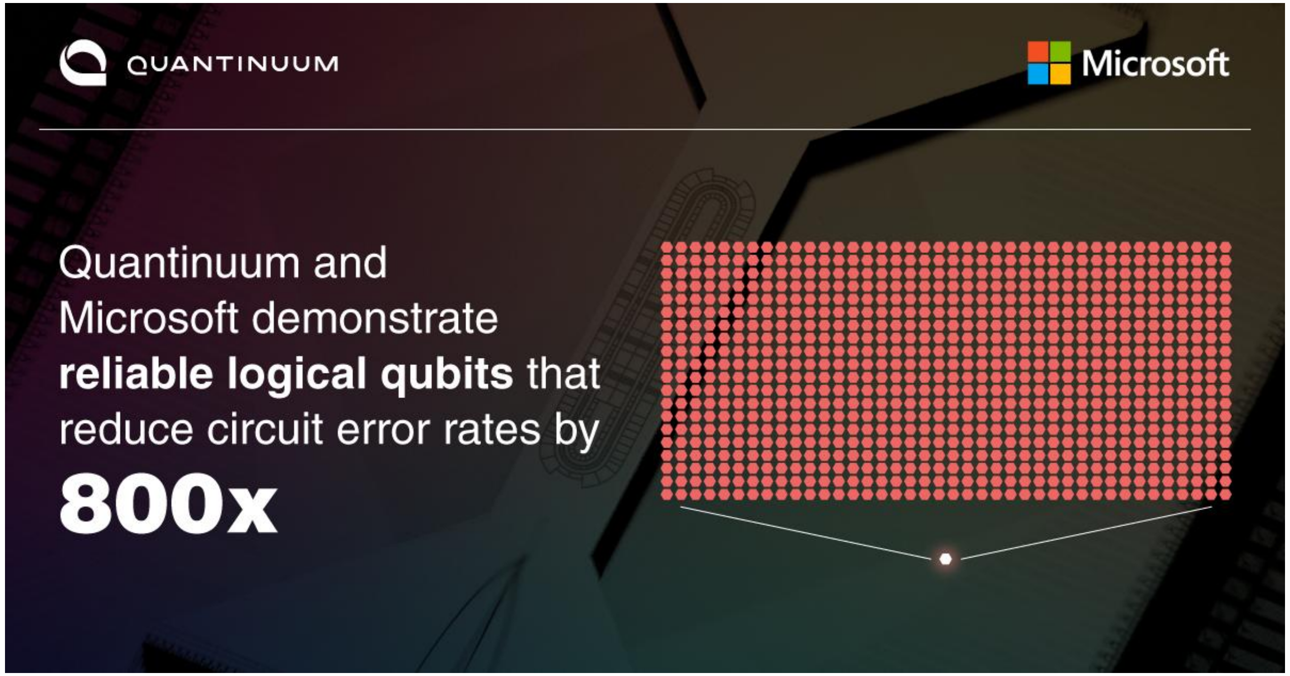
Recent breakthroughs in QC



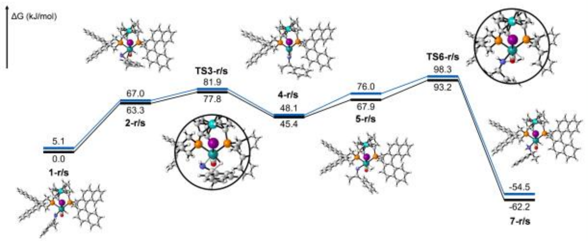
Google Logical Qubit Breakthrough Paves Way for Large Scale Quantum Computing

August 27, 2024

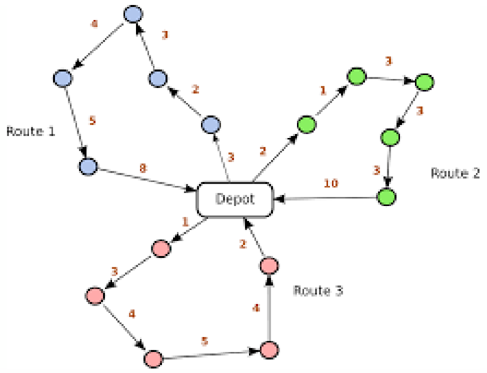
BY QUANTUM NEWS

Quantum computing applications

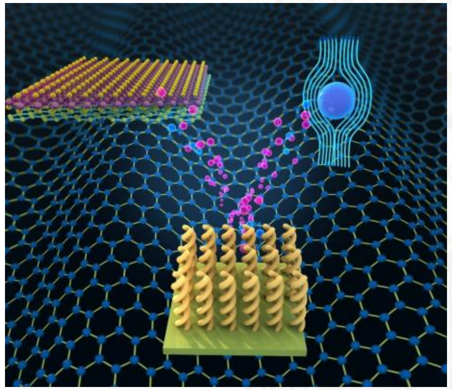
Chemistry



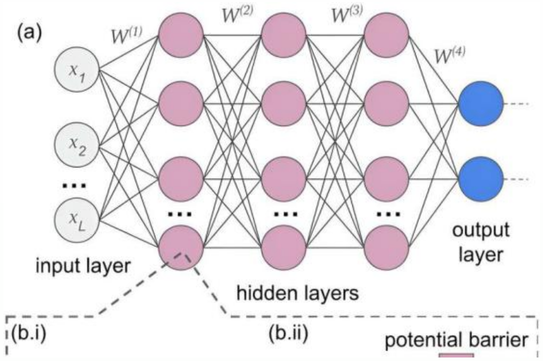
Optimization



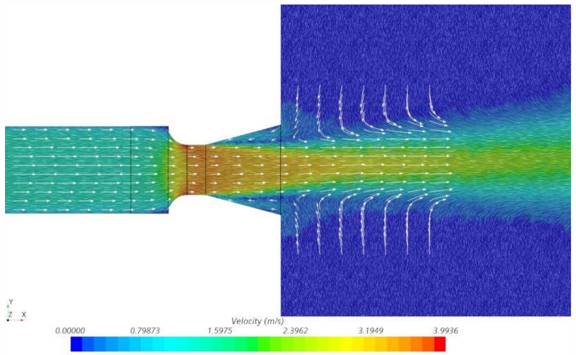
Material science



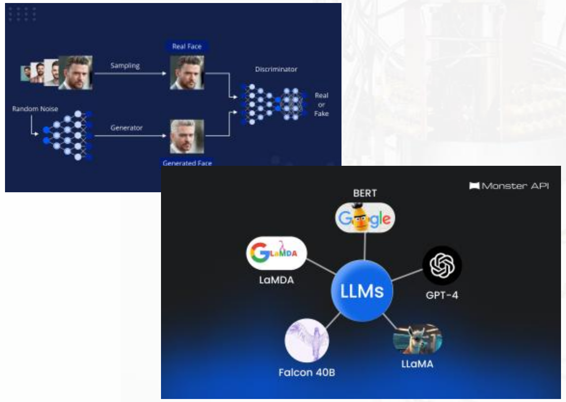
Quantum ML



Quantum simulation

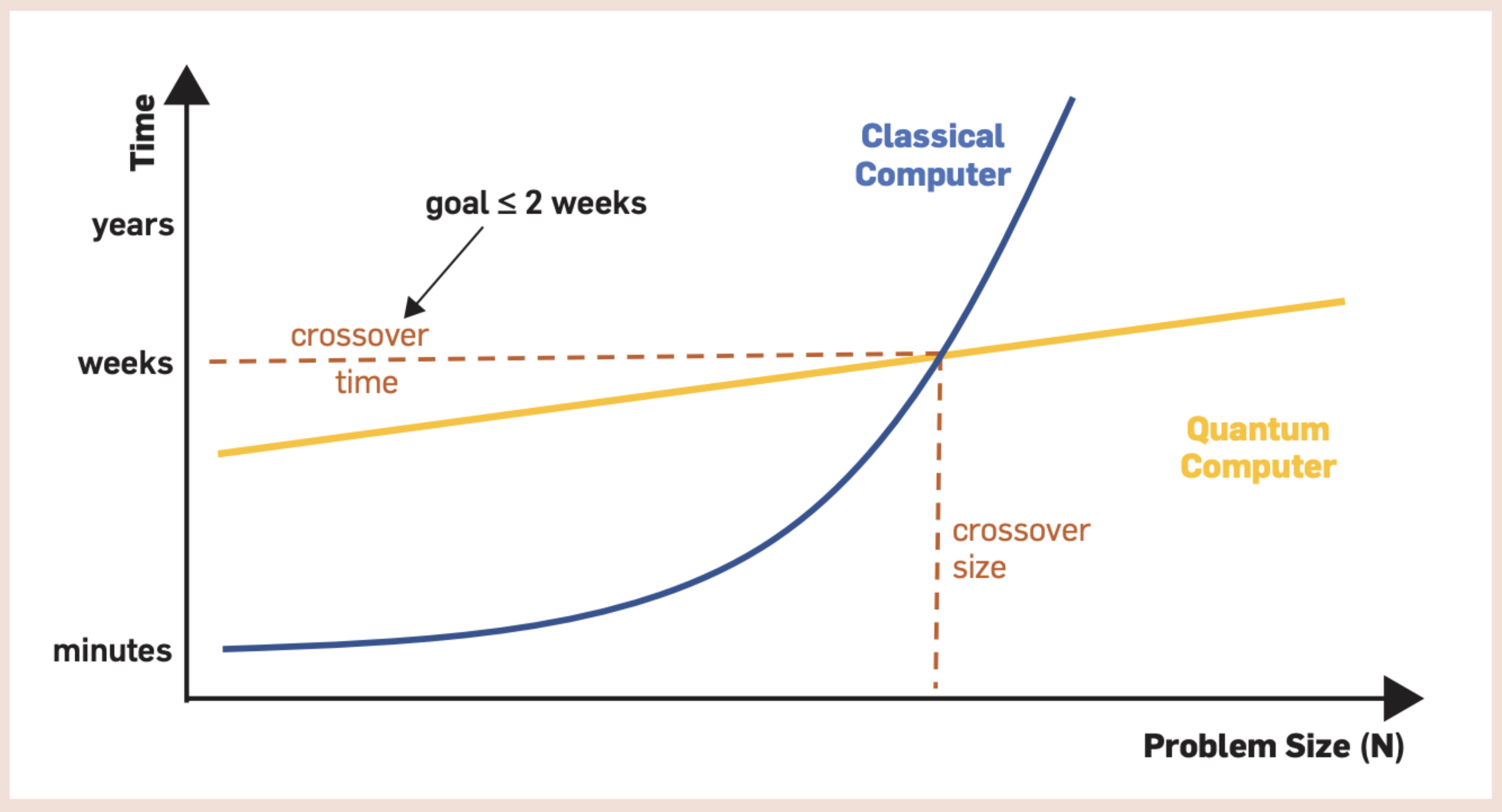


Quantum GenAI



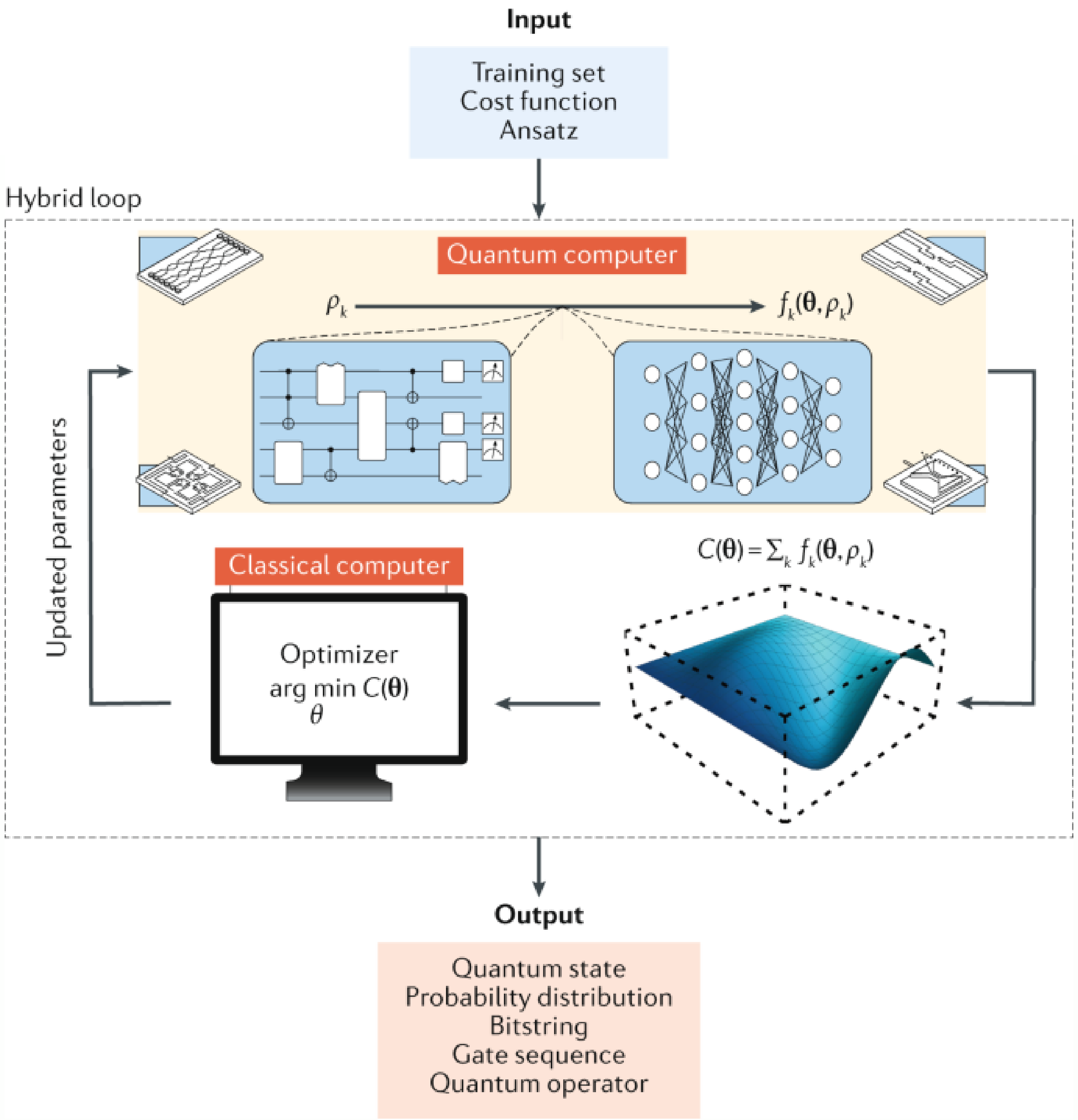
Disentagling hype from practicality

“the most promising candidates for quantum practicality are small-data problems with **exponential** speedup. Specific examples where this is the case are quantum problems in chemistry and materials science”



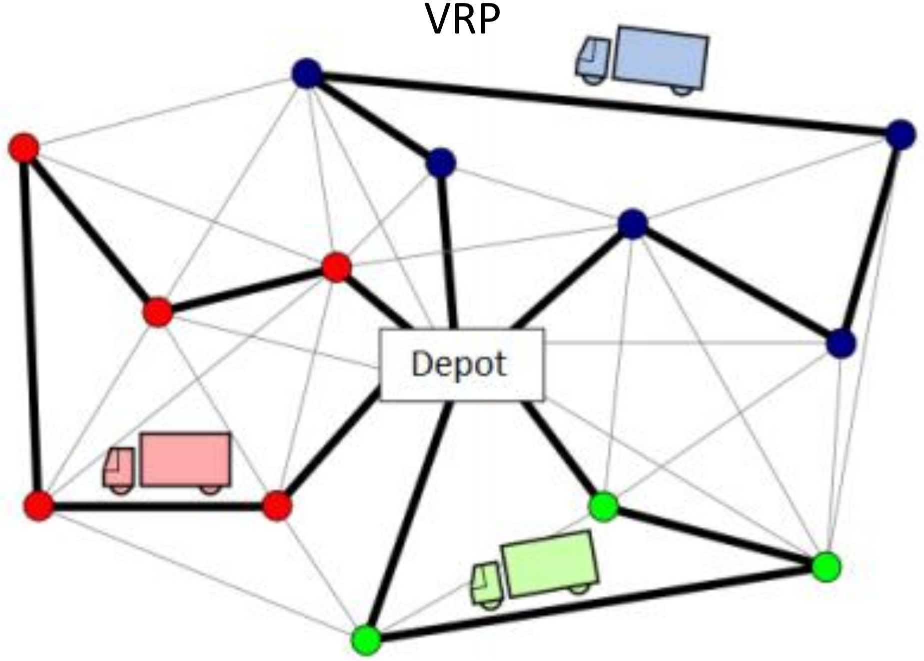
Hoefler, Torsten, Thomas Häner, and Matthias Troyer. "Disentangling hype from practicality: On realistically achieving quantum advantage." *Communications of the ACM* 66, no. 5 (2023): 82-87.

Variational quantum algorithms (VQAs)



A VQA is an algorithm that is based on the variational method based on a series of educated guesses, in the form of parameterized quantum circuits, with each guess being refined by classical optimizers until an approximate solution is found.

Vehcile routing problem using quantum computing



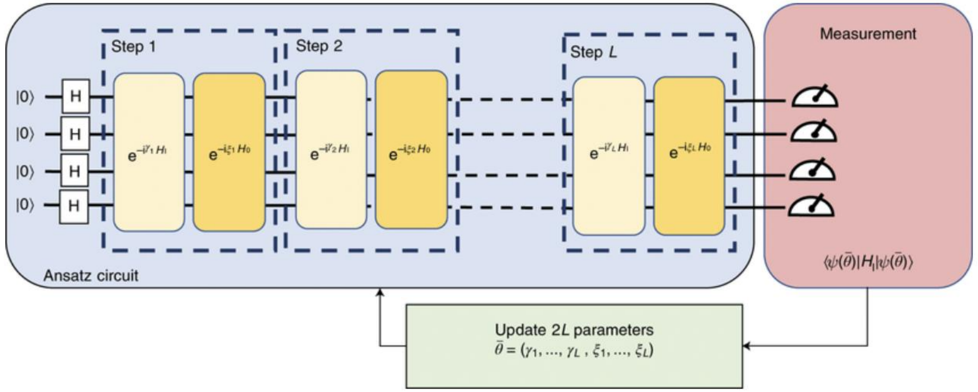


Fig. 2. Overall Structure of QAOA.

Problem	VQE	QAOA	Classical
Nodes=3 Vehicles=2	20.01	20.01	20.01
Nodes=4 Vehicles=2	24.34	23.86	23.86
Nodes=5 Vehicles=2	11713.48	98.26	98.26

TABLE I

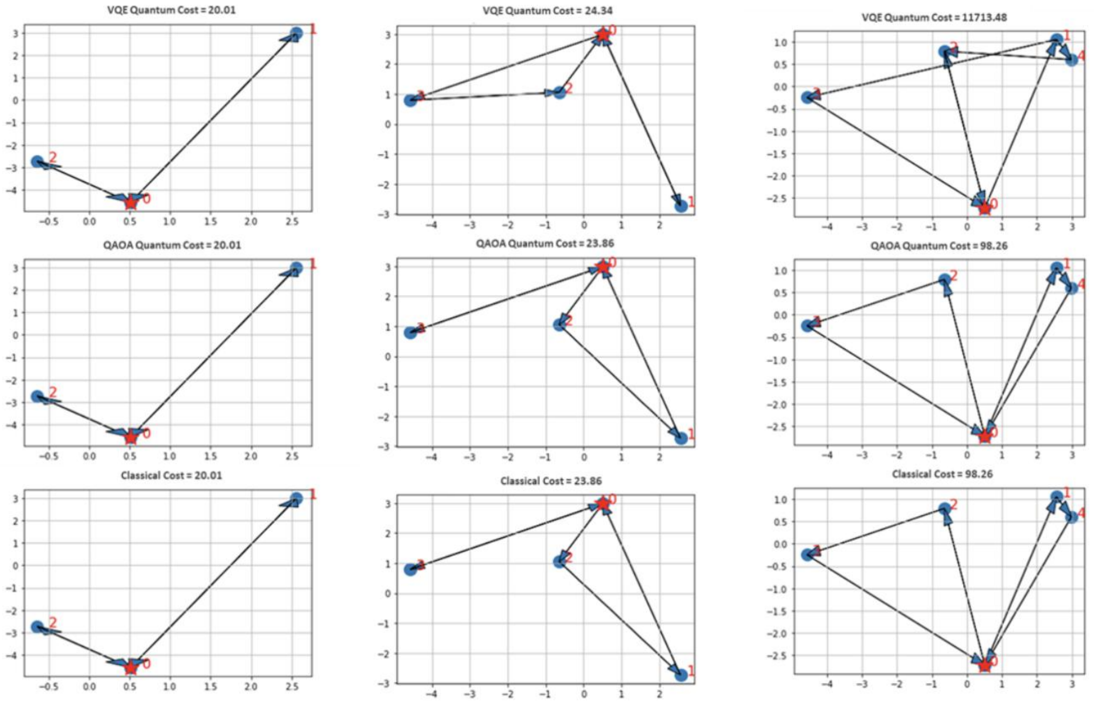


Fig. 4. Comparison of VRP solutions obtained by VQE, QAOA, and classical

Alsaiyari, Muhammad, and **Muhamad Felemban**. "Variational Quantum Algorithms for Solving Vehicle Routing Problem." In *2023 International Conference on Smart Computing and Application (ICSCA)*, pp. 1-4. IEEE, 2023.

Quantum-speedup for non-linear PDEs

Problem Formulation

Governing Equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho v^2 + p - r) = 0$$

$$\frac{\partial}{\partial t}\left[\rho\left(e + \frac{v^2}{2}\right)\right] + \frac{\partial}{\partial x}\left[\rho v\left(e + \frac{v^2}{2}\right) + pv - \tau + \frac{\kappa \partial T}{\partial x}\right] = 0$$

After conservation

non-linear partial form

$$\frac{\partial U}{\partial t} + \frac{\partial F[U, \frac{\partial U}{\partial x}]}{\partial x} = J[U]$$

Mathematical methods

non-linear ordinary form

$$\frac{dU}{dt} = f(U)$$

By integrating over N_k intervals:

$$y_{i+1}(j) = y_i(j) + N_k \sum_{l=1}^{N_k - 1} \frac{h}{N_k} \int_0^1 f\left(l_{i,l}(j,u)\right) du$$

Task: compute a bounded function $I(j,t)$ to approximate the exact solution $U(j,t) \approx y_{i+1}$ for a specific interval $0 \leq t \leq T$ with respect to the initial condition $I(j,0) = U(j,0) = U_0(J)$.

Experiments: Mean-Value Estimating Using QAEA

Initialize a quantum state that's in superposition → Define the probability distribution of measuring the target state → Measure and extract the estimated value

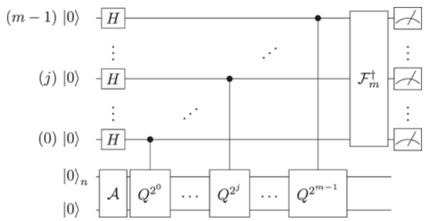


Fig. 1: QAEA circuit

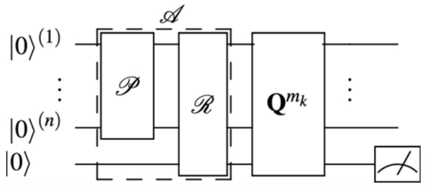


Fig. 2: Decomposed QAEA circuit

```
q0: ────────o─H─X─o─X─H─o────────
q1: ─────o─|─H─X─o─X─H─|─o─────
q2: ──o─|─|─H─X─o─X─H─|─|─o──
q3: ─Z─RX─RX─RX─RX─X─Z─X─RX─RX─RX─RX─
```

Fig. 3: 4-qubit quantum circuit implementing f

```
q0: ────────o─H─X─X─H─o────────
q1: ─────o─|─H─X─X─H─|─o─────
q2: ──o─|─|─H─X─X─H─|─|─o──
q3: ─Z─RX─RX─RX─RX─H─RX───RX─RX─RX─
```

Fig. 4: Circuit Fig. 3 after applying gate merging technique

```
q0:      ──────────────────────[─o─H─X─]─o─[─X─H─o─]───────────────── ...
q1:      ────────────[─o─H─X─]─|─|───────|─o─|──────|─|─[─X─H─o─]──────── ...
q2:      ─[──o─H─X─]─|─|──────|─|─|──────|─o─|──────|─|─|─────|─|─[─X─H─o─ ...
q3:      ─[─Z─RX─────]─[─RX─────]─[─RX─RX─X─]─Z─[─X─RX─RX─]─[─────RX─]─[─────RX ...

q0: ... ──
q1: ... ──
q2: ... ─]─
q3: ... ─]─
```

Fig. 5: Circuit Fig. 3 after applying gate fusing technique

Qibo Original Circuit	
Number of Qubits	4
Circuit Depth	12
Number of Gates	24
Estimated Value	**0.27**
***Qibo* Optimized Circuit using Gate Merging**	
Number of Qubits	4
Circuit Depth	11
Number of Gates	22
Estimated Value	**0.27**
***Qibo* Optimized Circuit using Gate Fusing**	
Number of Qubits	4
Circuit Depth	7
Number of Gates	7
Estimated Value	**0.27**
***Qibo* Optimized Circuit using Both Methods**	
Number of Qubits	4
Circuit Depth	5
Number of Gates	5
Estimated Value	0.27
***Pennylane* Original Circuit**	
Number of Qubits	7
Number of Gates	842
Estimated Value	0.30

Table 1: Results of Simulation on Qibo and Pennylane platforms

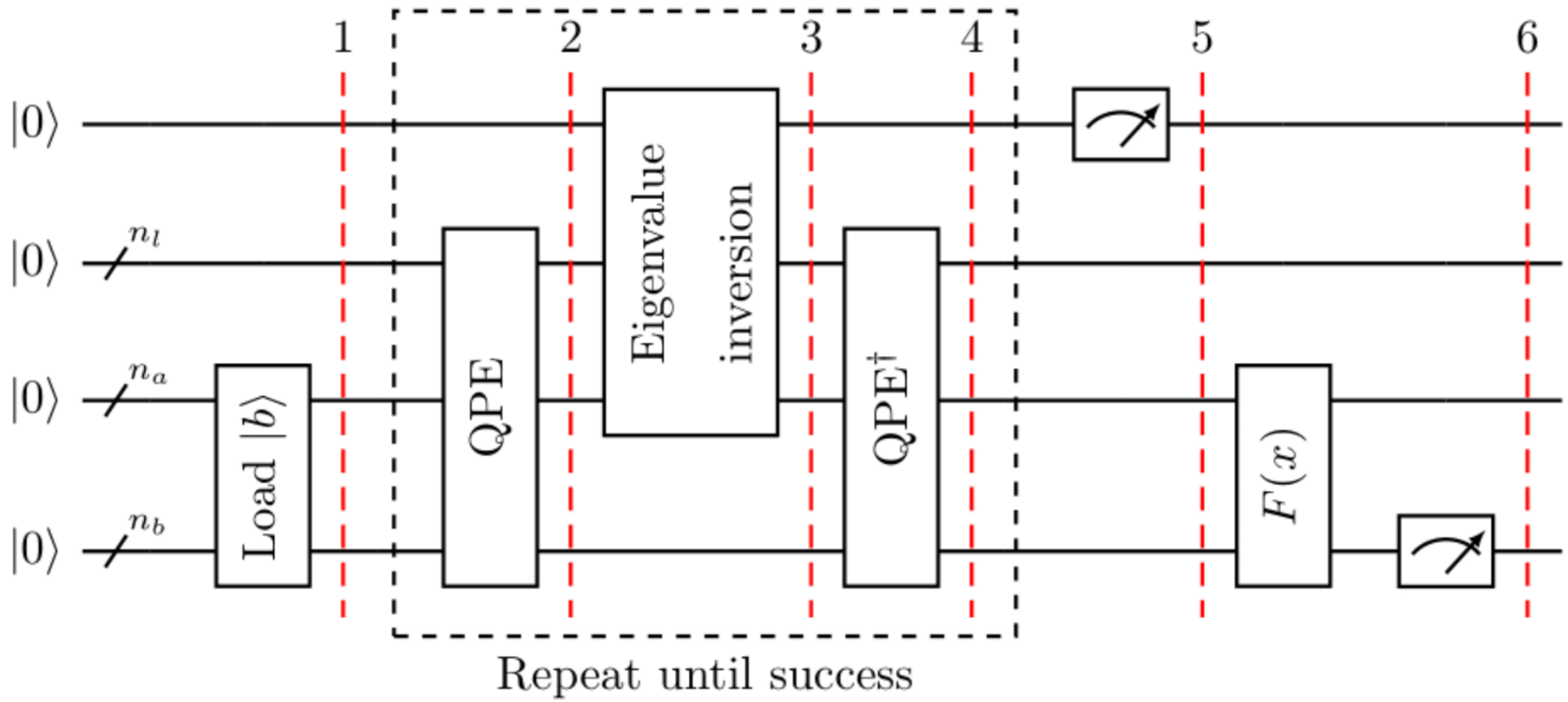
PI: Shuroog Al-Ogbi – Researcher, IRC-ISS

Solving linear systems with quantum computing

Solve $Ax = b$

$$O(\log(N)\,\kappa^2/\epsilon)$$

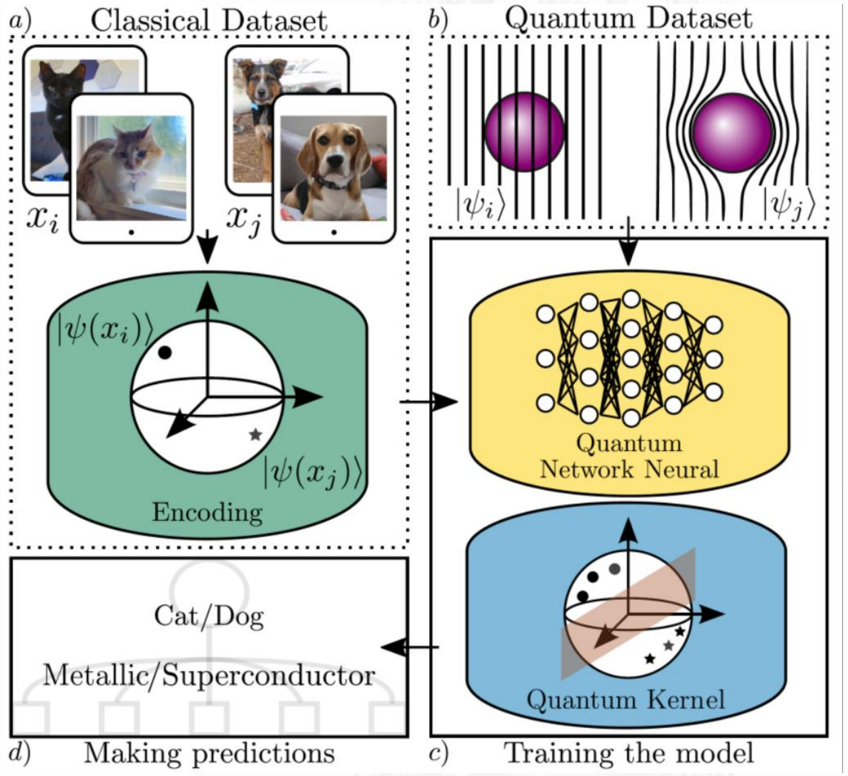
HHL Algorithm



Duan, Bojia, Jiabin Yuan, Chao-Hua Yu, Jianbang Huang, and Chang-Yu Hsieh. "A survey on HHL algorithm: From theory to application in quantum machine learning." Physics Letters A 384, no. 24 (2020): 126595

Quantum machine learning

- The development of quantum machine learning was heavily biased by conventional approaches to quantum computing, and search for the **computational speed-up**
- This has now evolved into several **new directions** of how advantage can be achieved
- Possible advantages (space-time complexity):
  - computational (training)
  - expressivity
  - generalization
  - learning
  - sampling
  - memory



DOI: 10.1039/D2CS00203E (Review Article) *Chem. Soc. Rev.*, 2022, **51**, 6475-6573

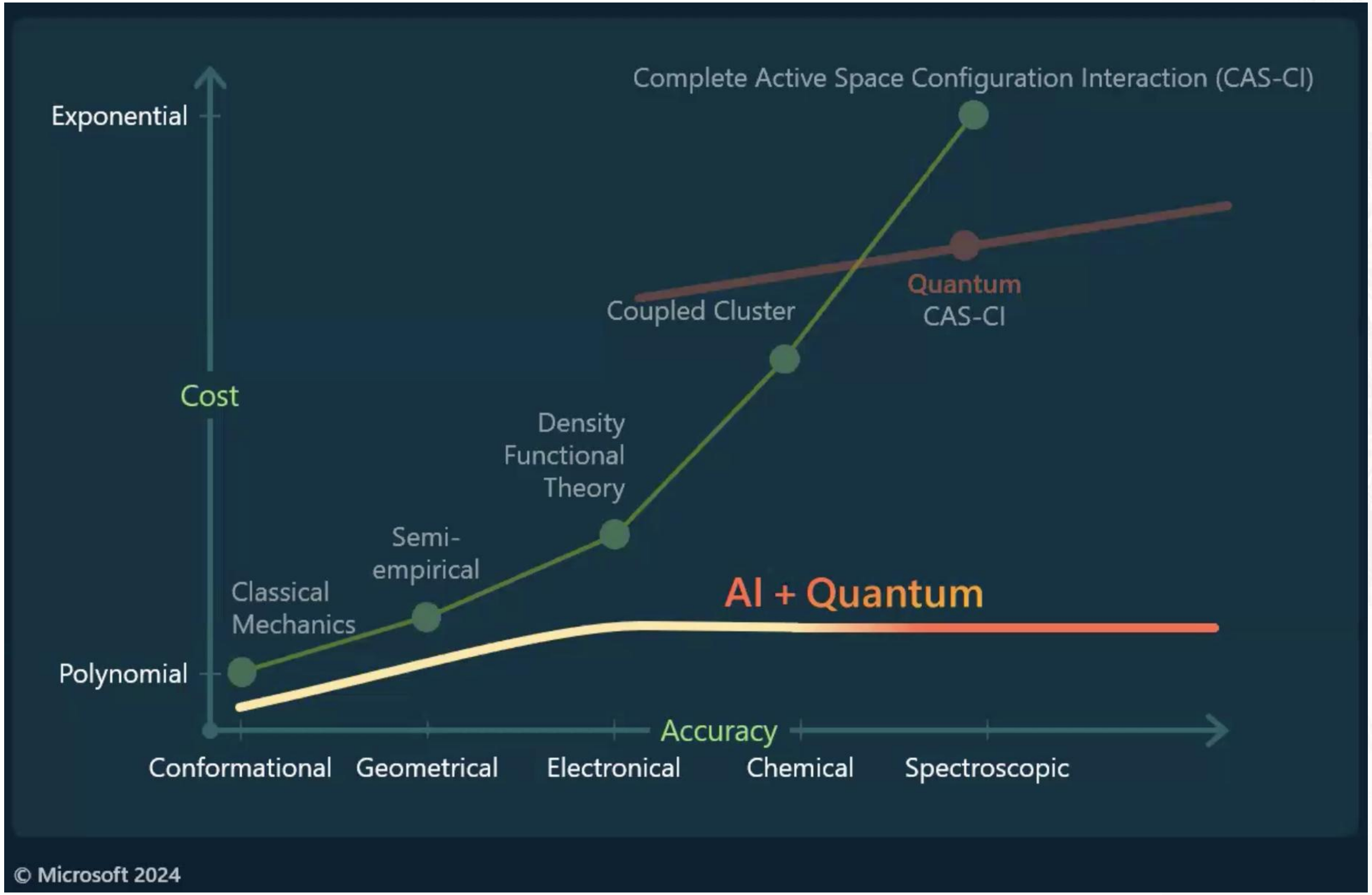
Quantum machine learning for chemistry and physics

Manas Sajjan [ab], Junxu Li† [bc], Raja Selvarajan† [bc], Shree Hari Sureshbabu‡ [bd], Sumit Suresh Kale‡ [ab], Rishabh Gupta‡ [ab], Vinit Singh‡ [ab] and Sabre Kais [*abcd]

Al-Ogbi, Shuroog, Abdulrahman Ashour, and Muhamad Felemban. "Quantum image classification on NISQ devices." In *2022 14th International Conference on Computational Intelligence and Communication Networks (CICN)*, pp. 1-7. IEEE, 2022.

Molecular modeling with quantum computing

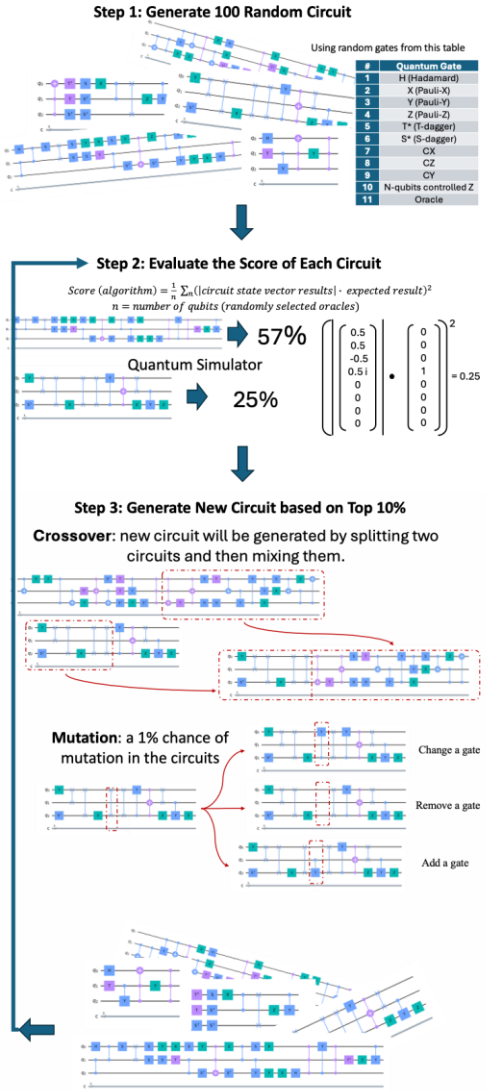
Jacob's ladder of quantum mechanical methods



*Taken from Matthias Troyer, Microsfot Keynote speech at IEEE QCE 2024

Discovery of quantum algorithms using genetic algorithms: exponential speedup via random sampling*

Methodology



#	Quantum Gate
1	H (Hadamard)
2	X (Pauli-X)
3	Y (Pauli-Y)
4	Z (Pauli-Z)
5	T* (T-dagger)
6	S* (S-dagger)
7	CX
8	CZ
9	CY
10	N-qubits controlled Z
11	Oracle

$$\text{Score}\ (algorithm) = \frac{1}{n}\sum_n (|\text{circuit state vector results}| \cdot \text{expected result})^2$$
n = number of qubits (randomly selected oracles)

Results

Our experiments used a genetic algorithm to discover oracle-based quantum algorithms in circuits with 3 to 8 qubits. By reducing evaluation time complexity from $O(2^n)$ to $O(n)$, we efficiently optimized larger circuits.

•**Grover's Algorithm Discovery**: The genetic algorithm identified the first iteration of Grover's algorithm in multiple experiments, proving the effectiveness of our approach. Sample of found circuits is shown in **Figure 1**.

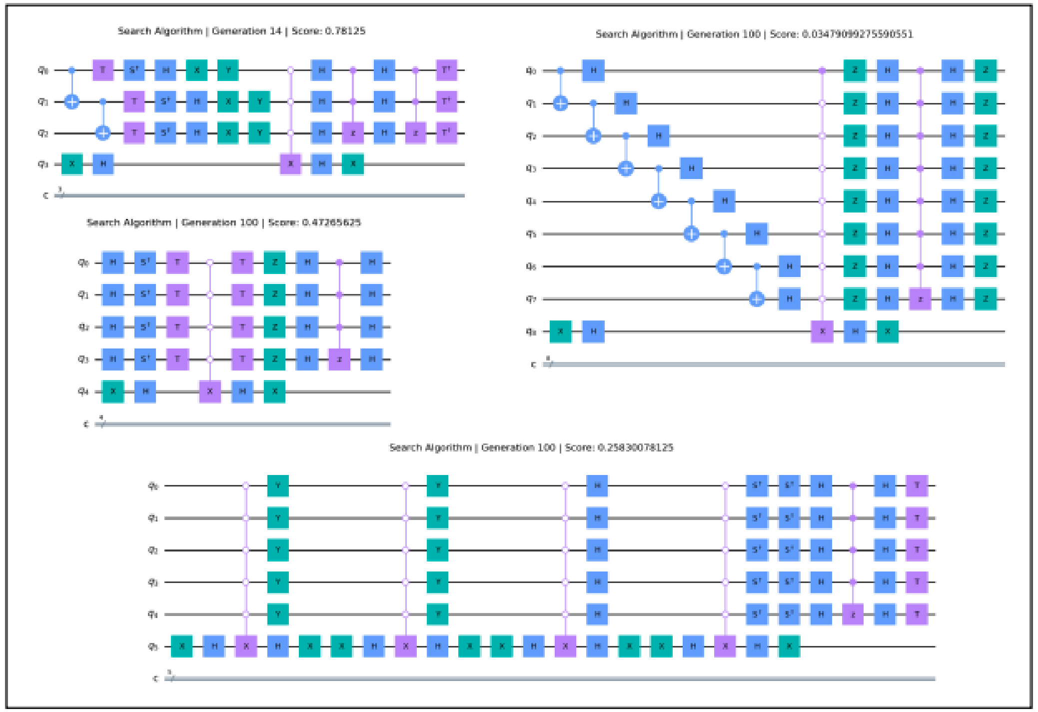


Figure 1: Sample of the best circuits found

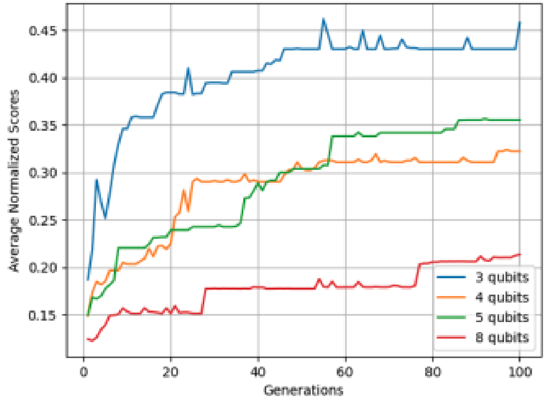


Figure 2: Average Normalized Scores Over Generations

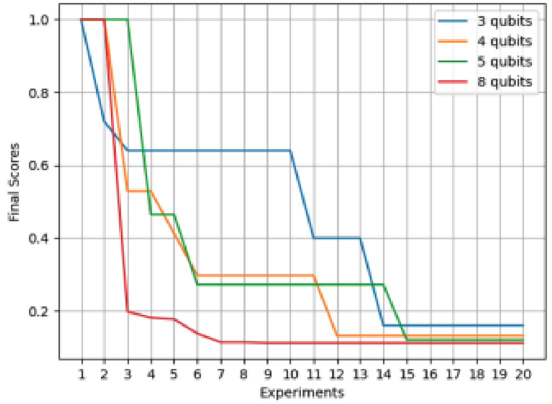


Figure 3: Final Normalized Scores of Each Experiment

PI: Tariq Almuqbil – MX Student

*Demo paper – IEEE QCE 2024

Mitigation of coherent losses in superconducting quantum circuits

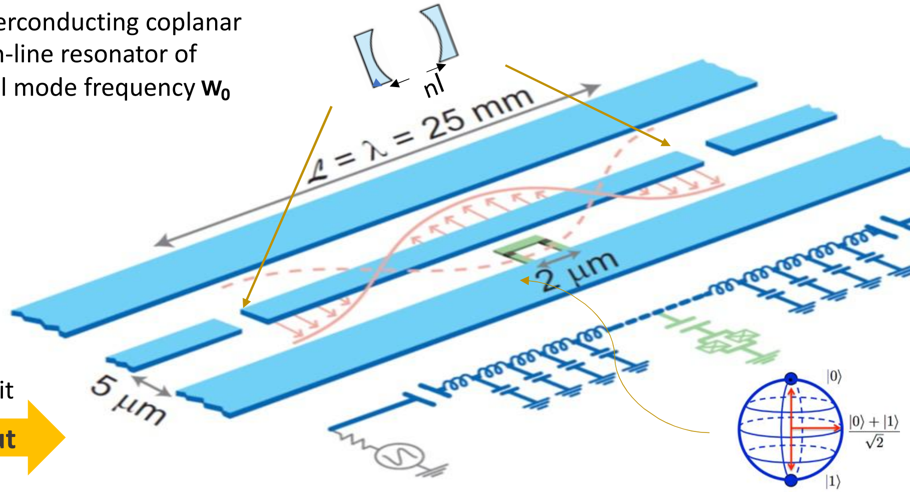
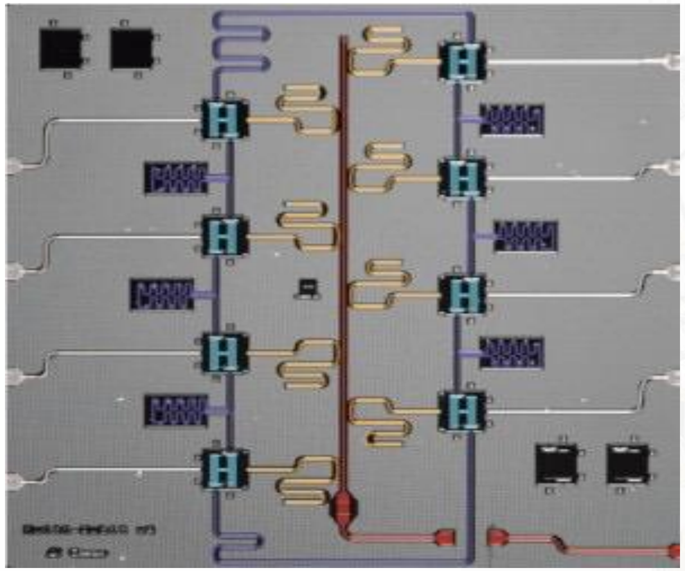


Figure. 1 Coupling between Qubits and CPW resonators



- 8 - Transman Qubits (Charge Qubit)
- CPW resonators :
  - Qubit-Qubit coupling bus resonators
  - Single-Qubit readout resonators
- Microwave drive lines
- Feedline resonators

Figure. 3 8-Qubits connected to superconducting resonators for controlling their quantum states that allow direct processing of information

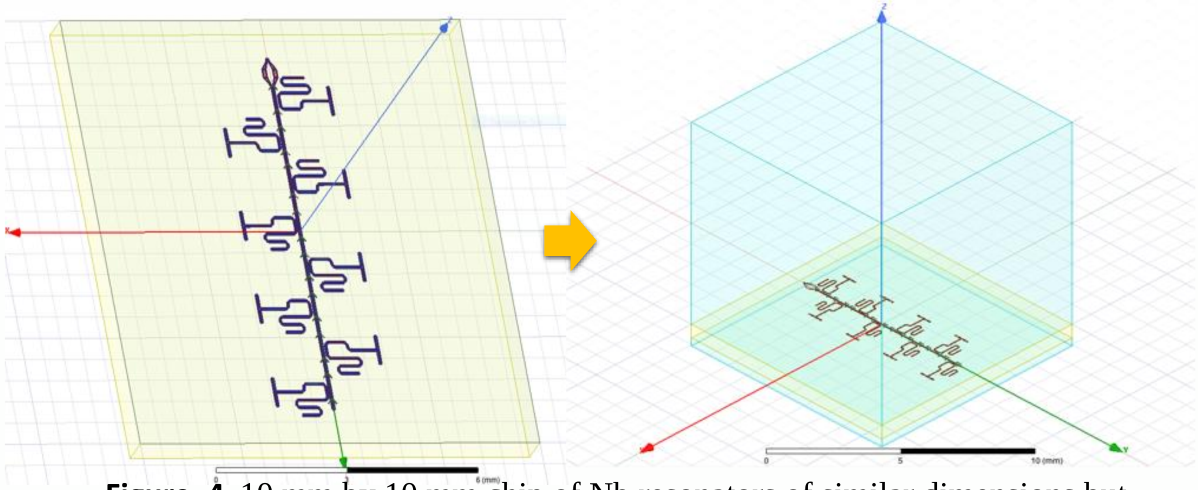


Figure. 4 10 mm by 10 mm chip of Nb resonators of similar dimensions but different positions on 674 μm thick Si substrate same as used in the 8-Qubit chip

PI: Dr. Saleem Rao

Quantum computing and technology group in IRC-ISS

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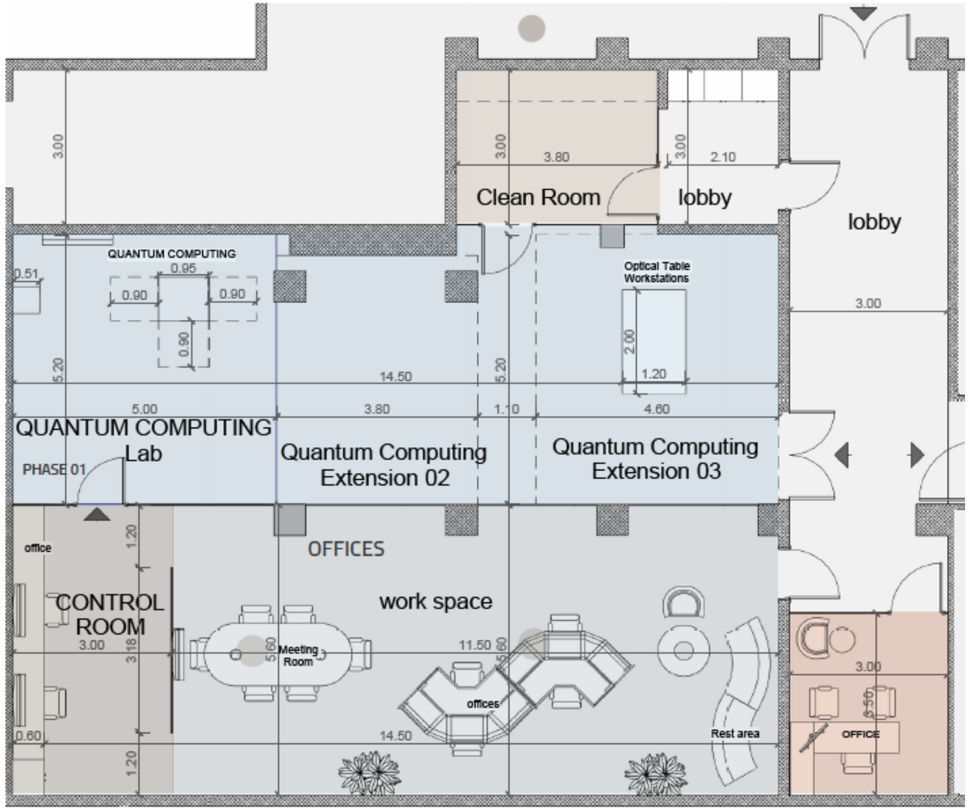
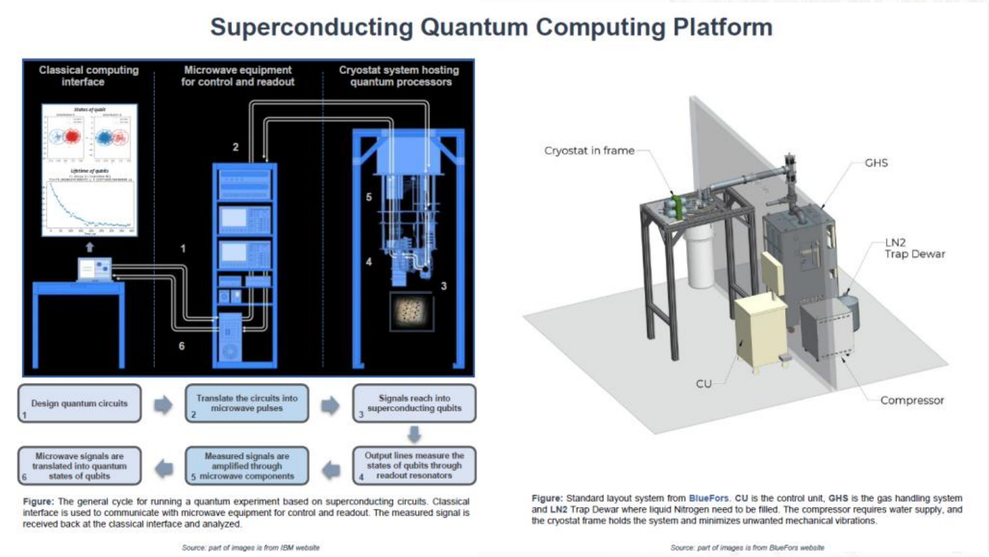
Dr. Abdulaziz Tabbakh

Dr. Alawi Alsaggaf

Superconducting quantum system lab

- This lab will be for research in superconducting based quantum systems
- The lab will used to characterize superconducting quantum chips, i.e., control and measure qubits





QC at KFUPM

CX and MX in Quantum Computing

Quantum Software

Quantum Middleware

Quantum Hardware

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From hype to hope

Solving real-world problems that will impact 100% of humans requires a combination of ..

Quantum ~~Computing~~ Technology

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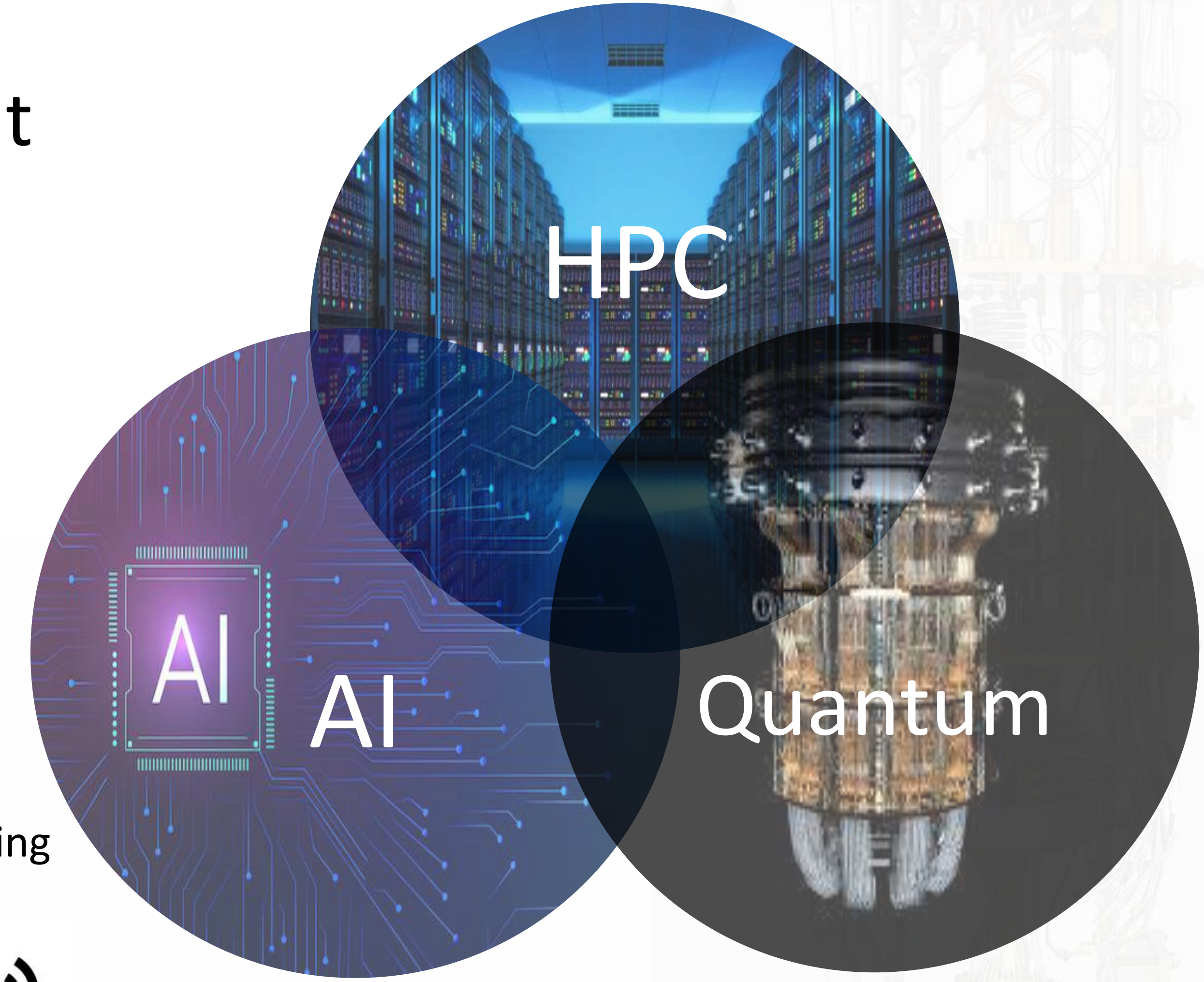

Thank you

For more information about our research

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