Introduction to Quantum Computing from Practical Point of View

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Quantum Computing in Academia

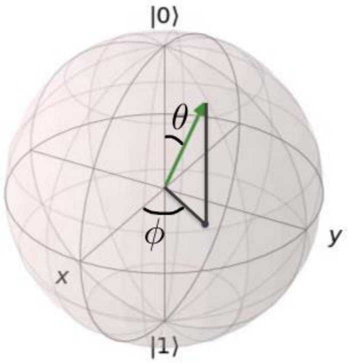
- ML: (classification, kernels, GAN etc..) [1]
- Networking (routing, task offloading, user association, channel assignment) [2]
- Biological sequence comparison algorithm [3]
- Chemistry and material science [4]
- Cybersecurity [5]
- Finance (optimization, stochastic modelling, ML) [6]
- Finding flows of a Navier-Stokes fluid through quantum computing [7]
- Overview: How can AI, LLMs and quantum science empower each other? [8]

[1] https://arxiv.org/abs/2304.09224 [2] https://arxiv.org/abs/2406.02240
[3] https://www.nature.com/articles/s41598-023-41086-5 [4] https://pubs.acs.org/doi/10.1021/acs.jctc.3c01043
[5] https://arxiv.org/abs/quant-ph/9508027 [6] https://arxiv.org/abs/2307.11230
[7] https://www.nature.com/articles/s41534-020-00291-0
[8] https://www.oezratty.net/wordpress/2024/ai-and-quantum-empower-each-other/

Introduction to Quantum Computing

Bit: Either 0 or 1

Qubit: $\alpha|0\rangle + \beta|1\rangle$ $\quad \alpha, \beta \in \mathbb{C}$, $\alpha^2 + \beta^2 = 1$



1. Instead of fixed zero/one state qubit has infinite many (we can efficiently encode data using one qubit).

Deutsch-Jozsa: $\alpha|0\rangle + \beta|1\rangle \longrightarrow \boxed{f(x)} \longrightarrow$

f(x) is constant or balanced?

2. Superposition of qubit states might be utilized to compute the output of the circuit in <u>parallel</u>.

Entanglement is a form of correlation between qubits.

- Without entanglement: $2N$ possibilities of quantum state, where N is the number of qubits
- With full entanglement 2^N possibilities

3. Entanglement provides us with <u>exponential grow</u> of possible quantum states. (Prime numbers factorization - classical approach require <u>exponential</u> time to solve, whereas quantum Shor's algorithm <u>polynomial</u>).

Evolution Stages of Quantum Computing

Noisy Intermediate Scale Quantum (NISQ) computing

Defined by John Preskill in 2018 [1]

Reasonable amount of qubits (50-100s) to solve some practical tasks, but with relatively high noise level, limiting its capabilities (in size and depth).

"NISQ devices are too large to be simulated classically, but also too small to implement quantum error correction".

Early Fault-tolerant Quantum Computing (EFTQC)

Used by Earl Campbell in 2021, described tradeoff in 2023 [2]

We must decide on a tradeoff between circuit size and fault tolerance.

Fault-tolerant Quantum Computing (FTQC)

Bright future

Require large amount of physical qubits to convert them to "noiseless" logical qubits using Quantum Error Correcting Codes (QECC).

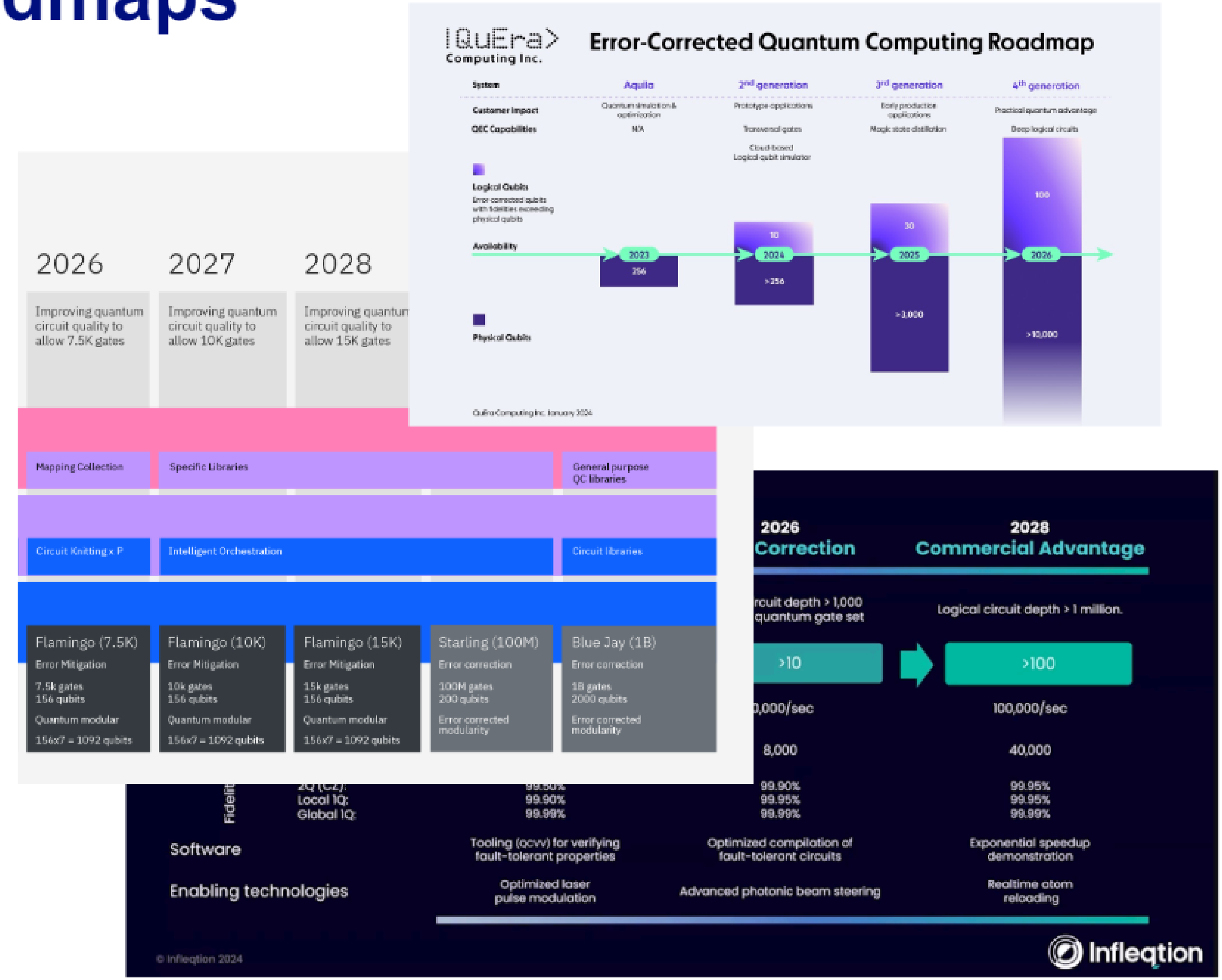
[1] - Quantum Computing in the NISQ era and beyond https://arxiv.org/abs/1801.00862

[2] - Early Fault-Tolerant Quantum Computing https://arxiv.org/abs/2311.14814

[3] - Overview comparison https://www.icvtank.com/newsinfo/886446.html?templateId=287088

Some Public FTQC Roadmaps

- **IBM** IBM Q™
  - 200 logical qubits by 2029
  - 100M Gates
- **Inflеqtion** Infleqtion
  - 100 logical qubits by 2028
  - 1-100M Gates
- **QuEra** |QuEra>
  - 100 logical qubits by ***2026***
  - Gates?



Source: https://arpa-e.energy.gov/sites/default/files/11_coffrin-updated-qc-hardware-overview-talk-2024-0503.pdf

Quantum Computing Algorithms

Optimization, Lowest energy state, QML [1]
(*Might be applicable nowadays and generally do not require deep understanding of Quantum physics*):

- Quantum algorithms to solve Quadratic Binary Unconstrained Optimization (QUBO) problems
- Quantum Approximate Optimization Algorithm (QAOA)
- Variational Quantum Eigensolver (VQE)
- Variational Quantum Algorithms (VQA)
  - Quantum-assisted NNs
- Anzatz-bazed (Kernels for SVM, etc..)

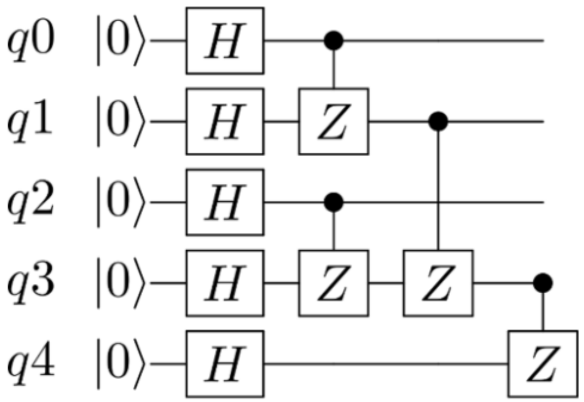
Fundamental algorithms [2]
(*Require a lot of logical qubits and a good understanding Of Quantum physics*):

- Quantum Fourier Transform (QFT)
- Shor’s
- Deutsch-Jozsa
- Grover
- HHL
- …

[1] – A comprehensive review of Quantum Machine Learning: from NISQ to Fault Tolerance https://arxiv.org/abs/2401.11351
[2] – Fundamental algorithms https://quantumalgorithmzoo.org/

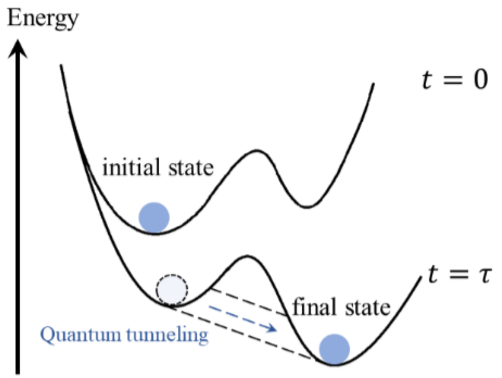
Types of Quantum Computers

Gate-based computations
("digital" quantum computing)



- Perform universal computations.
- Accommodate majority of quantum algorithms.
- Hardware agnostic (almost).

Adiabatic quantum computing
("analog" quantum computing) [2]



- Quantum annealing – find the lowest energy of the system (useful in optimization and system simulations).
- Quantum simulator – models the system under investigation.

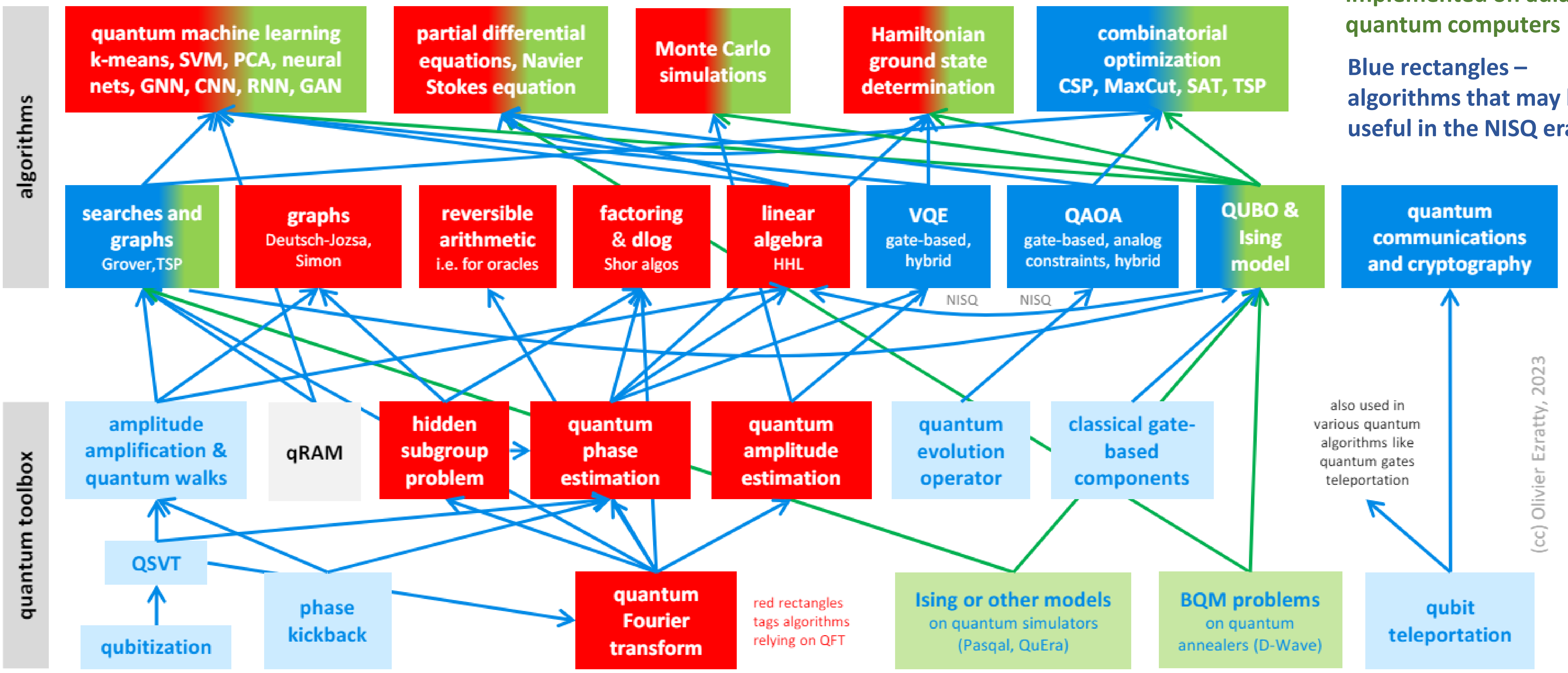
[1] - Adiabatic Quantum Computation is Equivalent to Standard Quantum Computation https://arxiv.org/abs/quant-ph/0405098
[2] - Adiabatic Quantum Computing https://arxiv.org/abs/1611.04471
[3] - Images https://www.ibm.com/quantum/blog/ & DOI:10.1101/2023.10.19.563028

Quantum Computing Algorithms

Red rectangles – algorithms based on QFT

Green rectangles – algorithms that might be implemented on adiabatic quantum computers

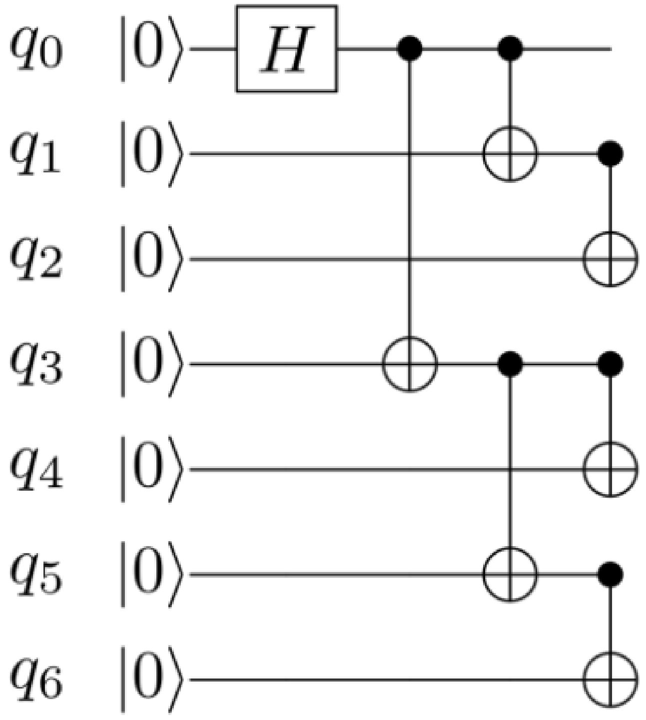
Blue rectangles – algorithms that may be useful in the NISQ era

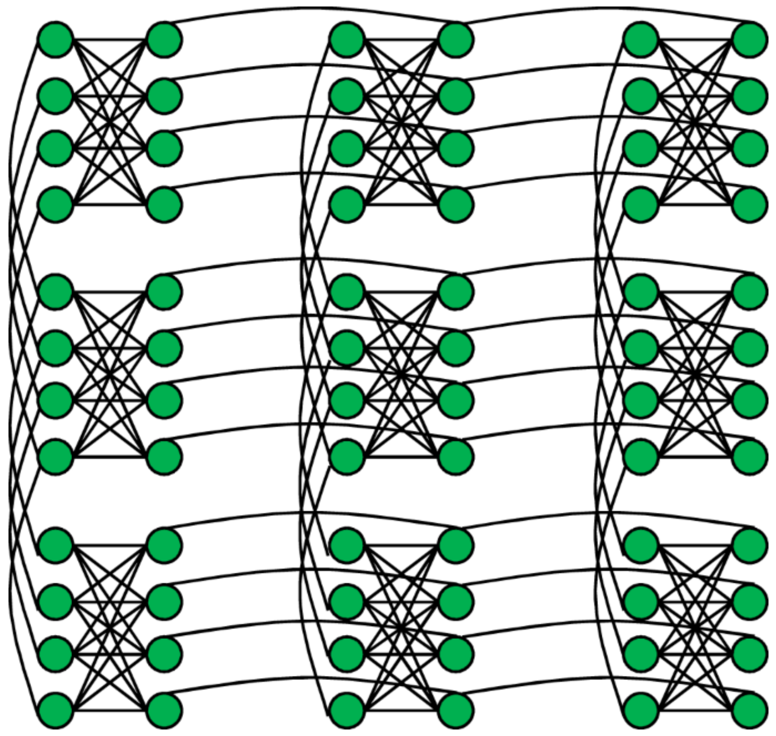


Source: https://www.oezratty.net/wordpress/2023/understanding-quantum-technologies-2023/

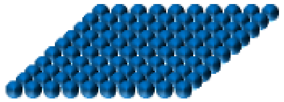
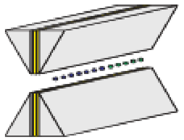
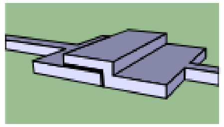
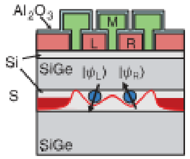
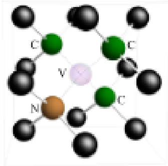
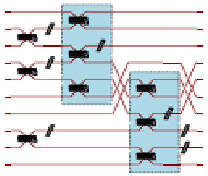
Most Important Characteristics of a Quantum Computer

- Number of qubits
- Connectivity
- Coherence time and gate execution time
- Gate Fidelity





Quantum Computing Platform Comparison

	atoms		electrons superconducting & spins			photons
						
	cold atoms	**trapped ions**	**superconducting**	**silicon**	**NV centers**	**photons**
qubit size	about 1 µm space between atoms	about 1 µm space between atoms	$(100\mu)^2$	$(100nm)^2$	$<(100nm)^2$	nanophotonics waveguides lengths, MZI, PBS, etc
best two qubits gates fidelities	99.5%	99.94%	99.68% (IBM Egret 33 qubits)	>99% (SiGe)	99.2%	98%
best readout fidelity	95%	99.99%	99.4%	99% (SiGe)	98%	50%
best gate time	≈1 ns	0.1 to 4 µs	20 ns to 300 ns	≈5 µs	10-700 ns	<1 ns
best T_1	> 1 s	0,2s-10mn	100-400µs	20-120µs	2.4 ms	∞ & time of flight
qubits temperature	< 1mK 4K for vacuum pump	<1mK 4K cryostat	15mK dilution cryostat	100mK-1K dilution cryostat	4K to RT	RT 4K-10K cryostats for photons gen. & det.
operational qubits	1,180 (Atom Computing)	32 (IonQ and Quantinuum)	433 (IBM) 176 (China)	12 (Intel) in SiGe	5 (Quantum Brilliance)-10	216 modes GBS (Xanadu)
scalability	up to 10,000	<100	1000s	millions	100s	100s-1M

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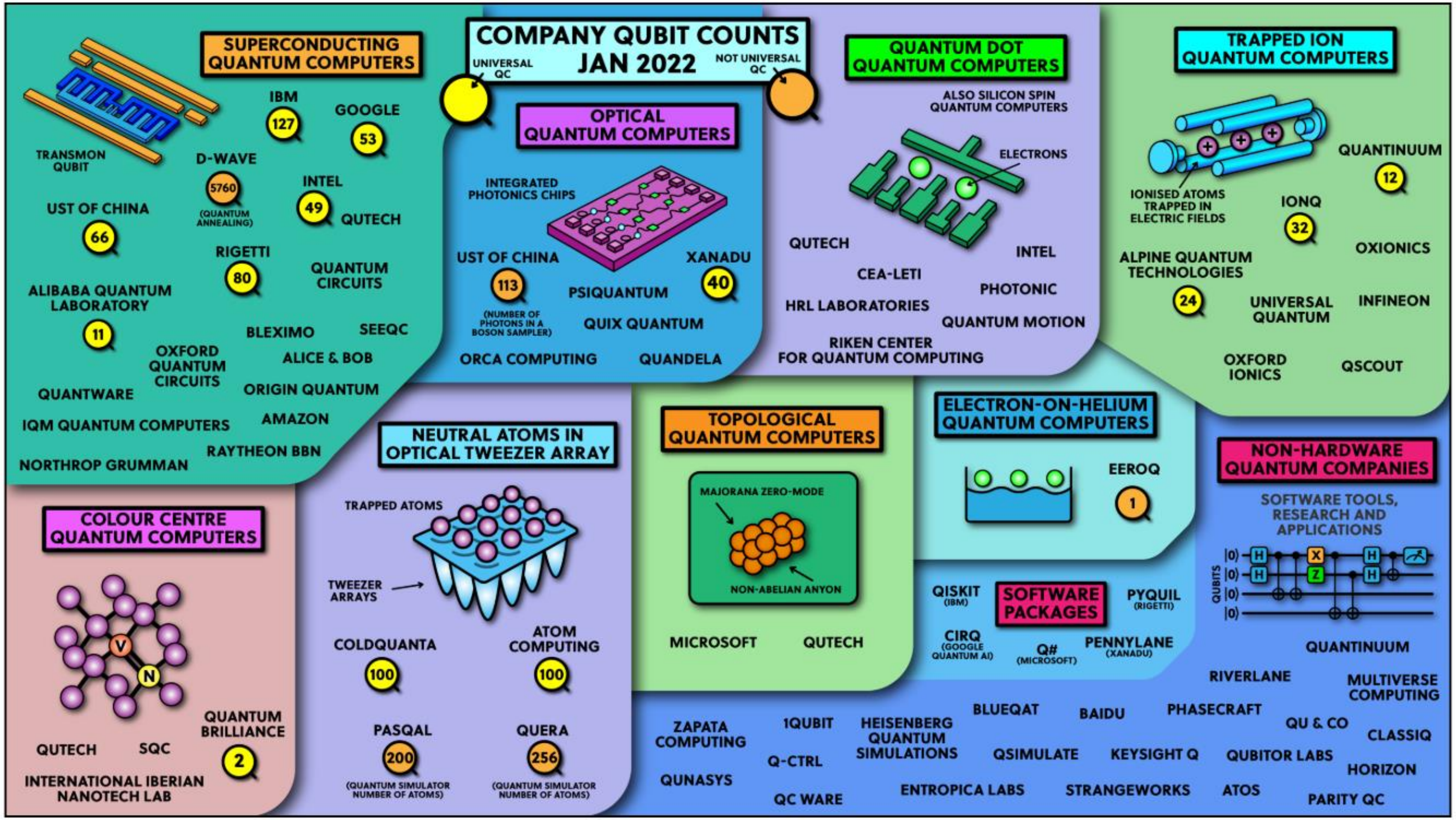
Types of Quantum Computers



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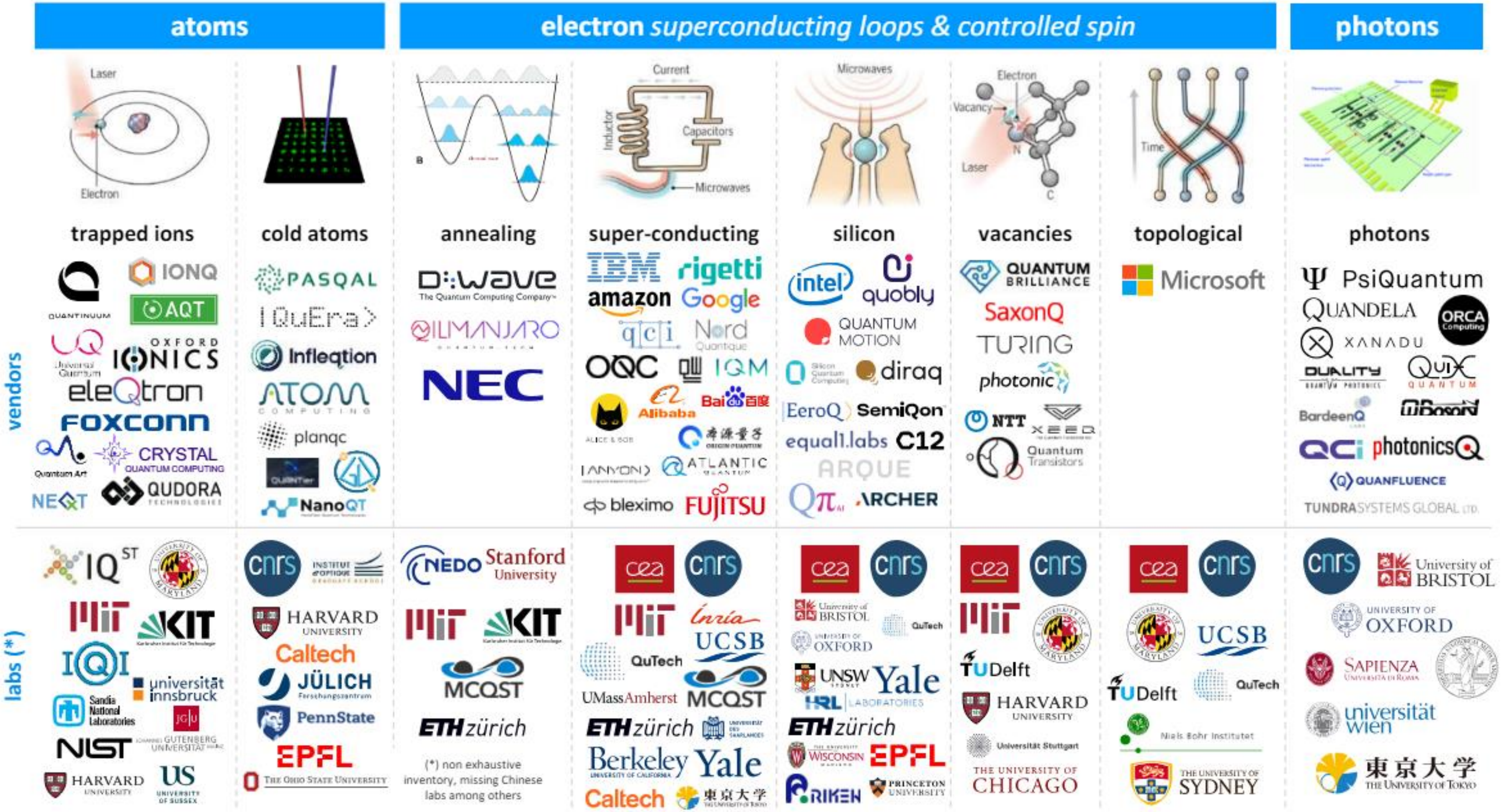
Quantum Computing Companies



Source: Understanding Quantum Technologies 2023 https://arxiv.org/abs/2111.15352

Quantum Programming Stack

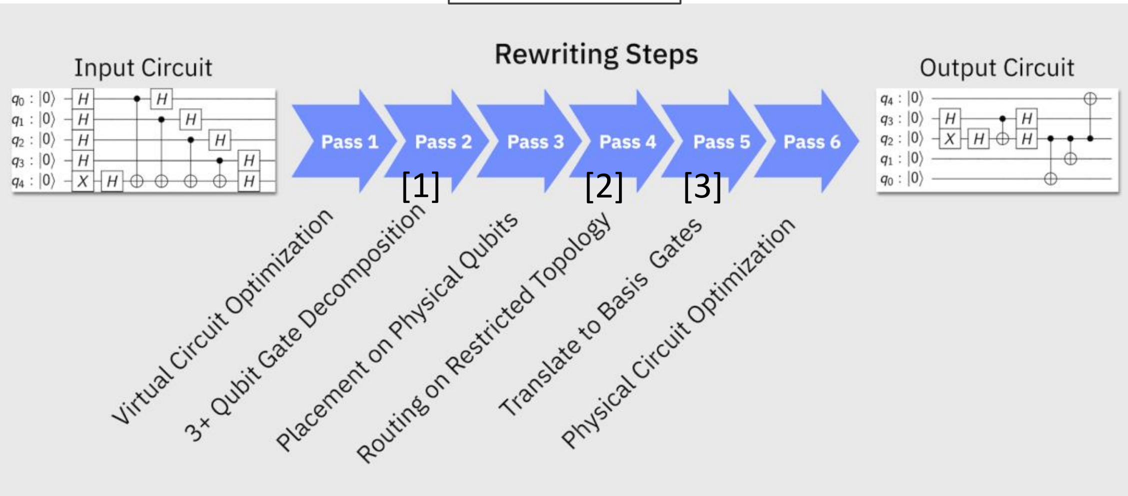
Algorithm depending on application

↓

Quantum source code

↓

Transpiler



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Hardware

Notes:
[1] – Currently we can physically implement only 1 and 2-qubit gates.
[2] – Remember about connectivity.
[3] – Any gate might be decomposed into combination of basis gates.

Source: https://docs.quantum.ibm.com/api/qiskit/1.0/transpiler

Quantum Programming Stack

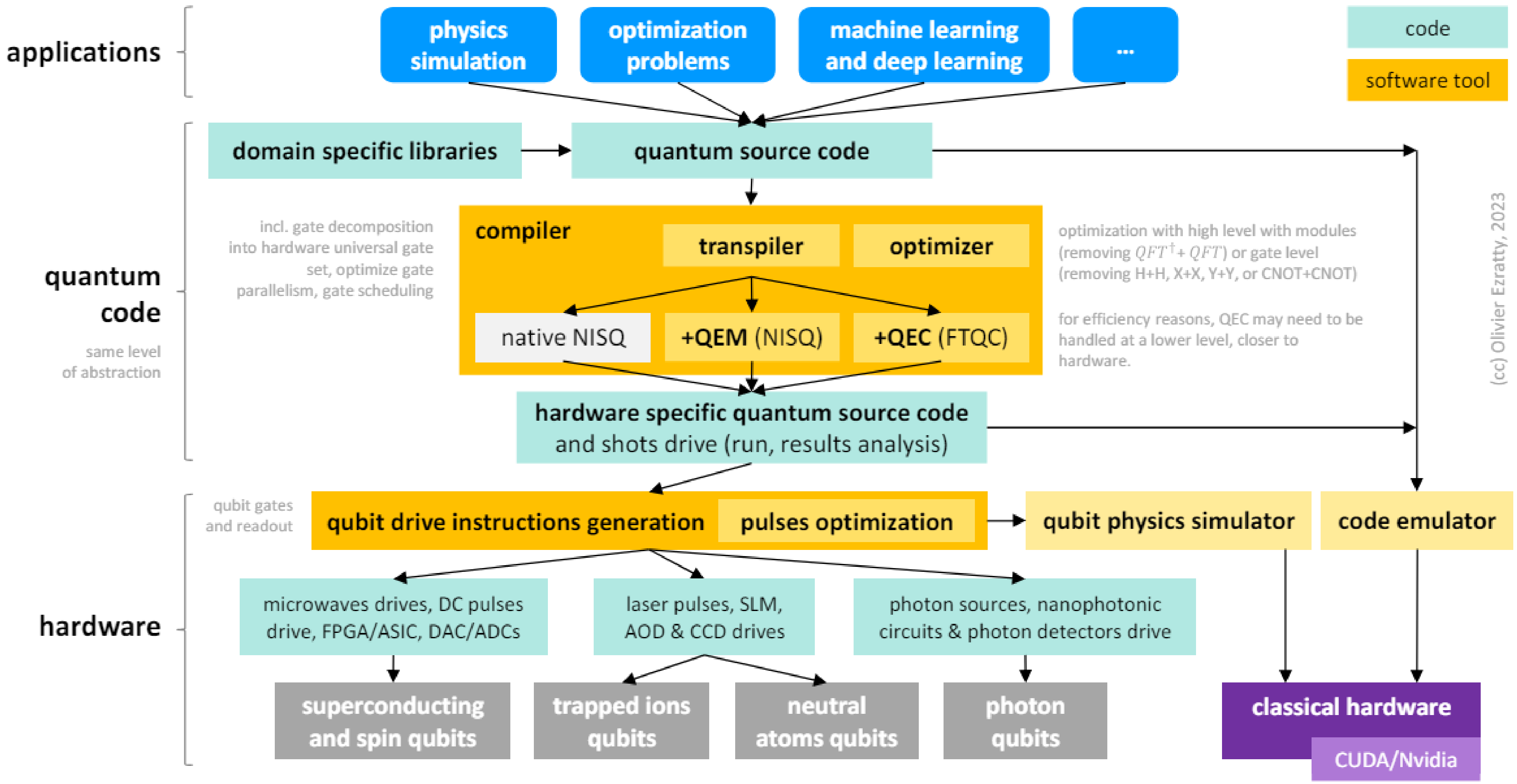


Figure 12: classification of quantum software engineering tools. (cc) Olivier Ezratty, 2023.

Source: Understanding Quantum Technologies 2023 https://arxiv.org/abs/2111.15352

Quantum Programming Languages

PENNYLANE

cuQuantum

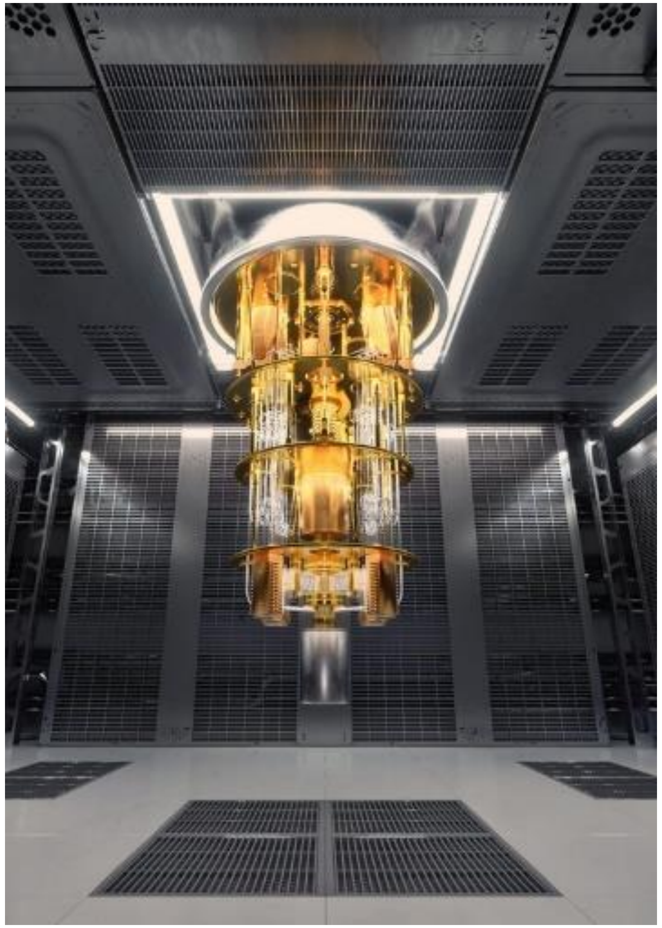
XACC

Qiskit

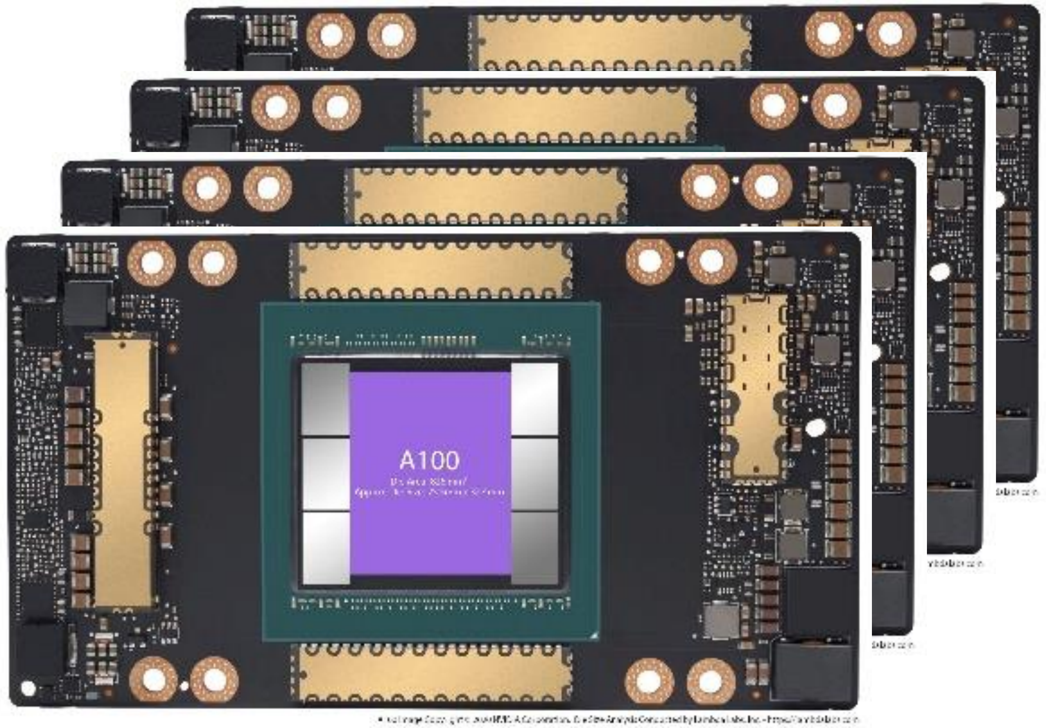
Cirq

Q#

Quantum vs Classical Computers in Practice



vs



Quantum vs Classical Computers in Practice

Complexity

- For high complexity, we need to remember that modern GPUs have billions of transistors. To compete effectively with them, quantum computing would require exponential speedup capabilities.
- For the low complexity tasks, classical computers remain more suitable.

- There is still a lack of reliable quantum memory, and there are no large-scale implementations.
- Quantum memory has very limited throughput compared to classical computers.
- Quantum mechanics adheres to the no-cloning theorem, which restricts the replication of quantum states.
- A qubit has a limited lifetime, which should be considered.

Memory

Execution time

- Operating a qubit is far more complicated than switching a transistor and is therefore orders of magnitude slower. Thus classical computers are more suitable for small tasks.

[1] Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage https://arxiv.org/abs/2307.00523

Conclusion

- In academia, ongoing research in quantum computing demonstrates its potential advantages across various fields.
- Currently, we are in a transitional phase from NISQ (Noisy Intermediate-Scale Quantum) to FTQC (Fault-Tolerant Quantum Computing).
- Algorithms are rapidly evolving, although many are still far from practical application.
- From a practical standpoint, quantum computing is best suited to efficiently solve problems with low memory requirements and in case of exponential speedups in complexity, particularly in fields such as chemical and biological simulations.

How to start?

- Long way: Find a suitable book for Quantum computing (Any modern one would be good)
- Short way: go to https://pennylane.ai/qml/ or https://learning.quantum.ibm.com/catalog/courses (You can find more on github)
- For detailed info: https://arxiv.org/abs/2111.15352
- Short overview: https://www.oezratty.net/wordpress/2023/understanding-quantum-technologies-2023/