Quantum Computing Today and Future Perspective

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Physics of Computation Conference (1981)

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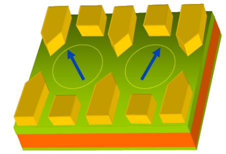
Where is QC now?

P.W. Shor, "Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer," SIAM Journal on Computing, vol. 26, pp. 1484–1509, 1999.

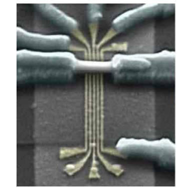
Shor's algorithm

1994-1995

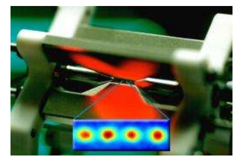
Quantum dots (Intel)



Majoranas (Microsoft)

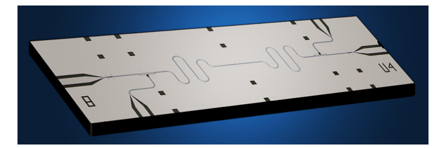


Trapped ions (IonQ)

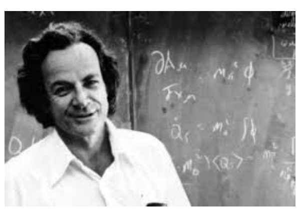


2012- present

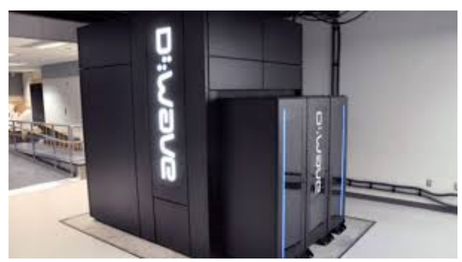
Superconducting (Google, Intel, IBM, Rigetti, Alibaba)



1981



1998-2000



Quantum annealing

Rigetti: 19 qubits (19Q)
IBM: 65 qubits (IBM Quantum Hummingbird)
IonQ: 32 qubits
Google: 54 qubits (Sycamore)

"Can physics be simulated by a universal computer?"

"...the problem is, how can we simulate the quantum mechanics?"

"Can you do it with a new kind of computer - a quantum computer?"

R. P. Feynman, "Simulating physics with computers," International Journal of Theoretical Physics, vol. 21, p. 467–488, 1982.

Google claimed to demonstrate 'quantum supremacy'

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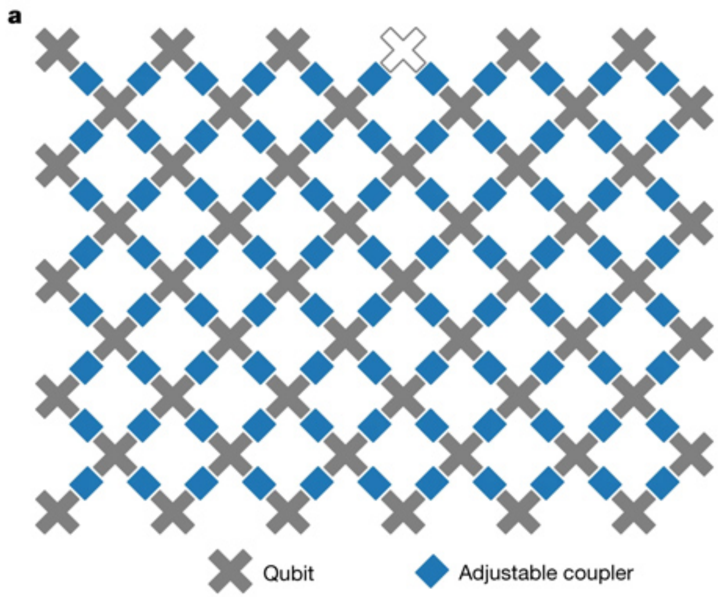
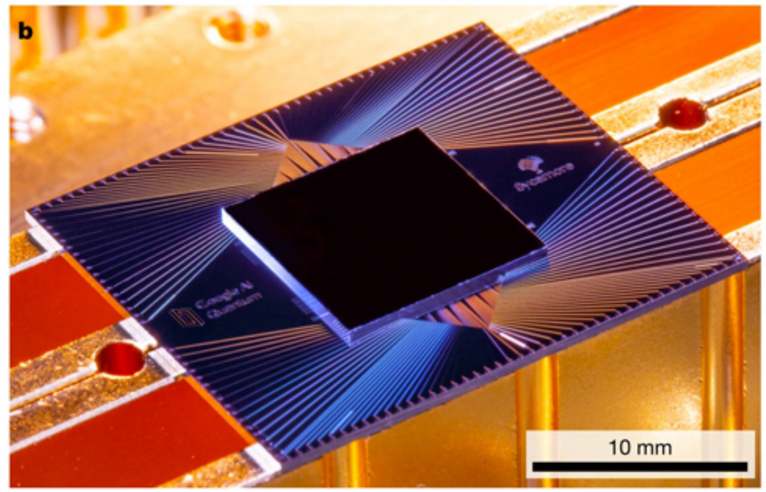
Google on quantum supremacy

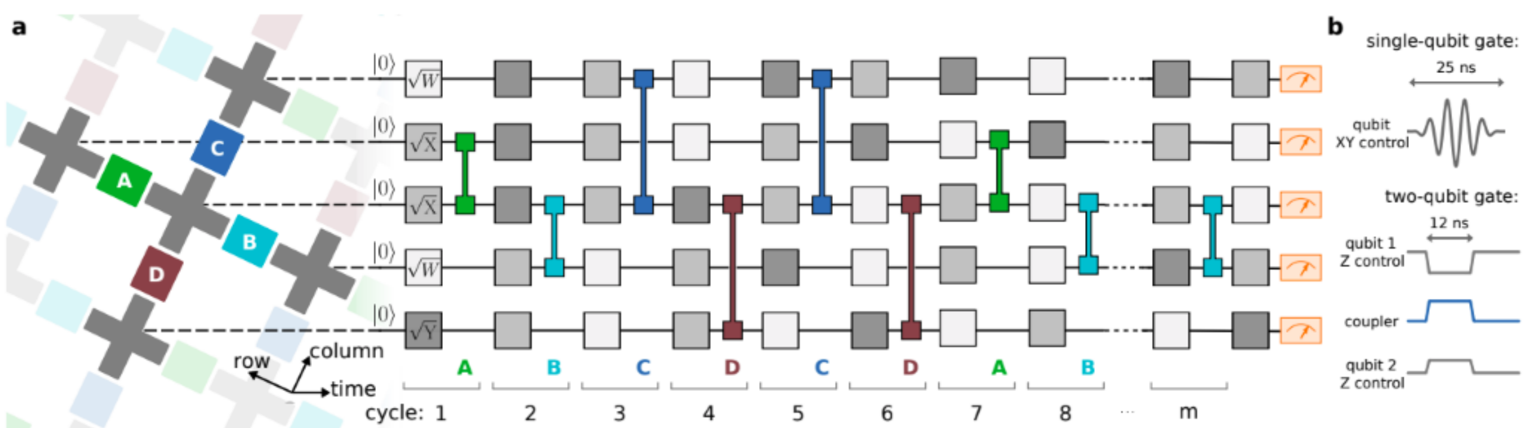




Sycamore processor

53 qubits

2^{53} (about 10^{16})



200 s vs. 10.000 years

F. Arute et al. "Quantum supremacy using a programmable superconducting processor." *Nature* 574.7779 (2019): 505-510.

https://www.youtube.com/watch?feature=youtu.be&v=FklMpRiTeTA&app=desktop

Google on quantum supremacy

- ”This experiment is used for two things: validating our quantum computer and for showing that quantum mechanics is really complex”
- “Errors do no depend on entanglement and computational complexity”
- “We expect that lower simulation costs than reported here will eventually be achieved”
- IBM on “Quantum Supremacy”(https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/): *We argue that an ideal simulation of the same task can be performed on a classical system in 2.5 days and with far greater fidelity*
- “This is the beginning of the NISQ era”

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Where is QC now?

NISQ era: Noisy Intermediate-Scale Quantum technology

John Preskill. arXiv:1801.00862, 2018

Here “intermediate scale” refers to the size of quantum computers which will be available in the next few years, with a number of qubits ranging from 50 to a few hundred.

“Noisy” emphasizes that there are unwanted interactions of the qubit with the environment and we have imperfect control over those qubits.

The noise will place serious limitations on what quantum devices can achieve in the near term.

Where is QC now?

Coherence times and gate error rates

EXHIBIT 7 | Overview of Leading Quantum Computing Technologies During the NISQ Era

	Leading technologies in NISQ era[1]		Candidate technologies beyond NISQ		
Qubit type or technology	**Superconducting[2]**	**Trapped ion**	**Photonic**	**Silicon-based[3]**	**Topological[8]**
Description of qubit encoding	Two-level system of a superconducting circuit	Electron spin direction of ionized atoms in vacuum	Occupation of a waveguide pair of single photons	Nuclear or electron spin or charge of doped P atoms in Si	Majorana particles in a nanowire
Physical qubits[4,5]	IBM: 20, Rigetti: 19, Alibaba: 11, Google: 9	Lab environment: AQT[6]: 20, IonQ: 14	**6×3[9]**	**2**	target: 1 in 2018
Qubit lifetime	**~50–100 µs**	**~50 s**	**~150 µs**	**~1–10 s**	target ~100 s
Gate fidelity[7]	**~99.4%**	**~99.9%**	**~98%**	**~90%**	target ~99.9999%
Gate operation time	**~10–50 ns**	**~3-50 µs**	**~1 ns**	**~1–10 ns**	–
Connectivity	Nearest neighbors	All-to-all	To be demonstrated	Nearest neighbor	–
Scalability	No major road-blocks near-term	Scaling beyond one trap (>50 qb)	Single photon sources and detection	Novel technology potentially high scalability	?
Maturity or technology readiness level	TRL[10] 5	TRL 4	TRL 3	TRL 3	TRL 1
Key properties	Cryogenic operation Fast gating Silicon technology	Improves with cryogenic temperatures Long qubit lifetime Vacuum operation	Room temperature Fast gating Modular design	Cryogenic operation Fast gating Atomic-scale size	Estimated: Long lifetime High fidelities

The Next decade in Quantum Computing – And How to Play
https://www.bcg.com/publications/2018/next-decade-quantum-computing-how-play.aspx

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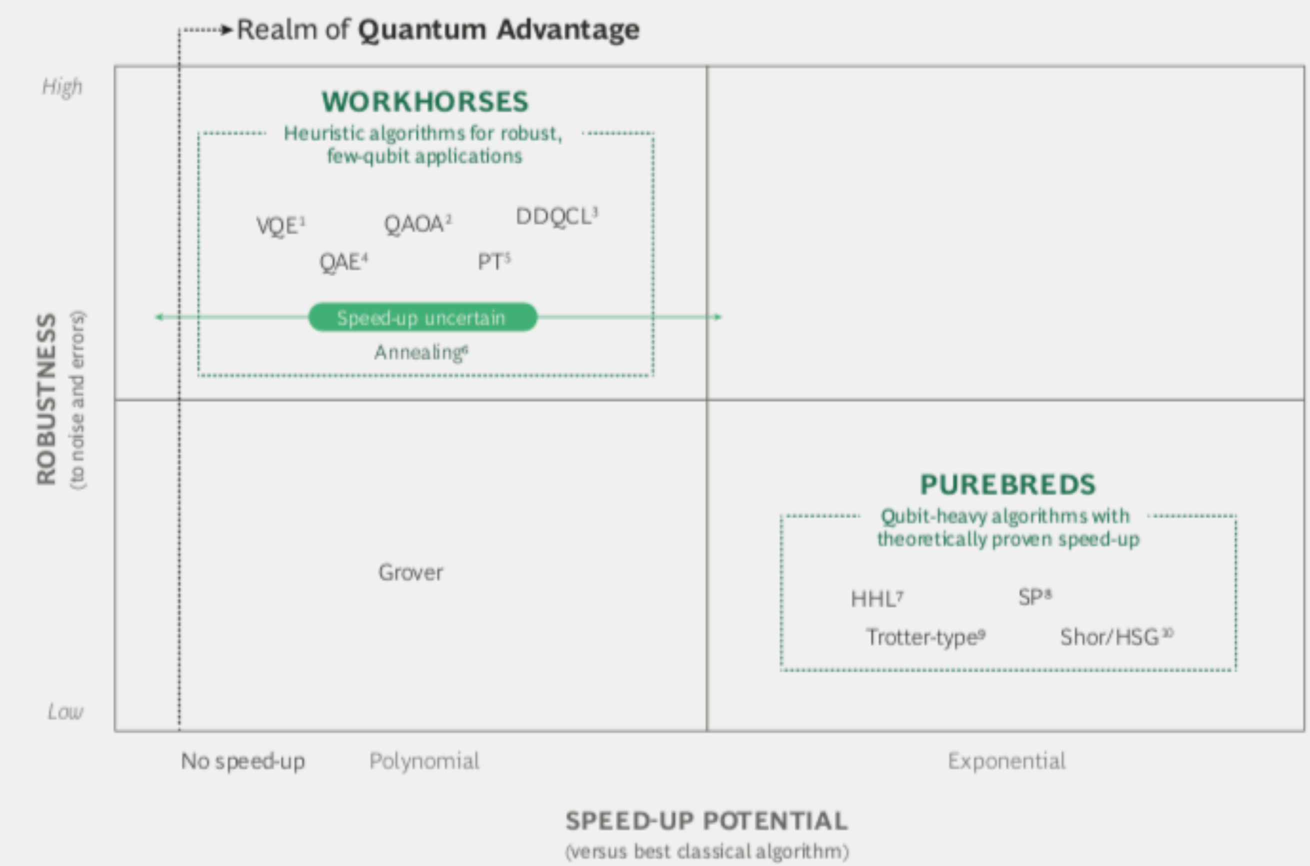
Where is QC now?

EXHIBIT 8 | Workhorse Algorithms Will Dominate During the NISQ Era



Sources: BCG analysis; expert interviews.
[1]Variational quantum eigensolver.
[2]Quantum approximate optimization algorithm.
[3]Data-driven quantum circuit learning for generative modeling in machine learning tasks.
[4]Quantum auto encoder, a compression algorithm for quantum data.
[5]Population transfer between computational states with similar energies for search and reverse annealing optimization.
[6]Optimization by quantum annealing as an alternative to circuit-based algorithms.
[7]Linear-system-solving algorithm devised by Harrow, Hassidim, and Lloyd.
[8]Semidefinite programming.
[9]Trotter-based algorithms for molecular simulation and adiabatic state preparation.
[10]Algorithms exploiting hidden-subgroup symmetries such as Shor's algorithm.

The Next decade in Quantum Computing – And How to Play
https://www.bcg.com/publications/2018/next-decade-quantum-computing-how-play.aspx

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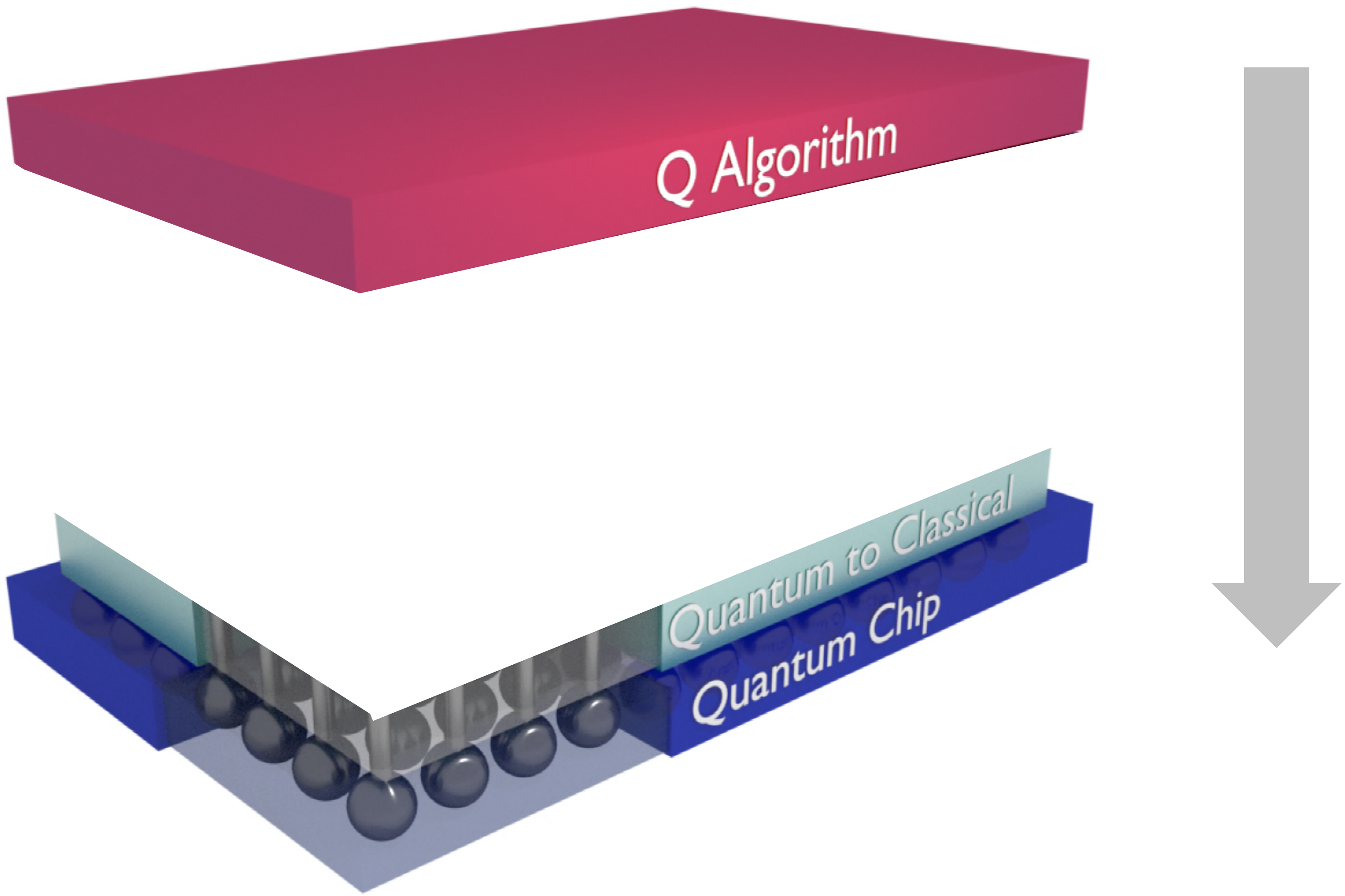
Circuit-based quantum computer

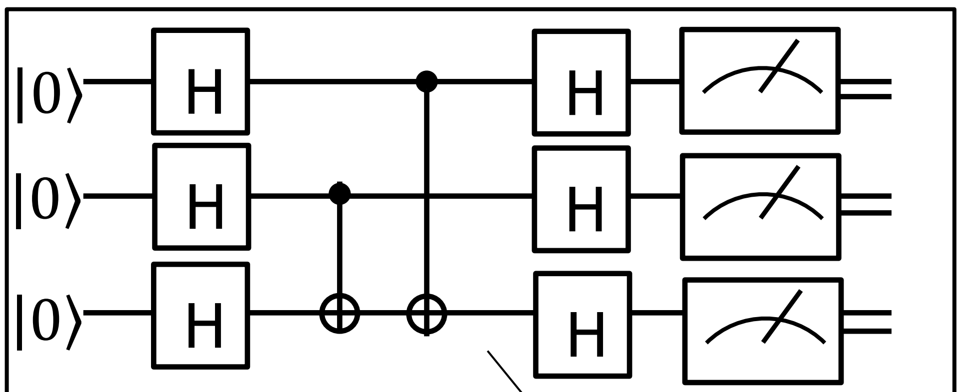


Circuit-based quantum computer

High-level language (Python)

```
qreg = eng.allocate_qureg(3)
Entangle | qureg
Measure | qureg
```

Low-level instructions

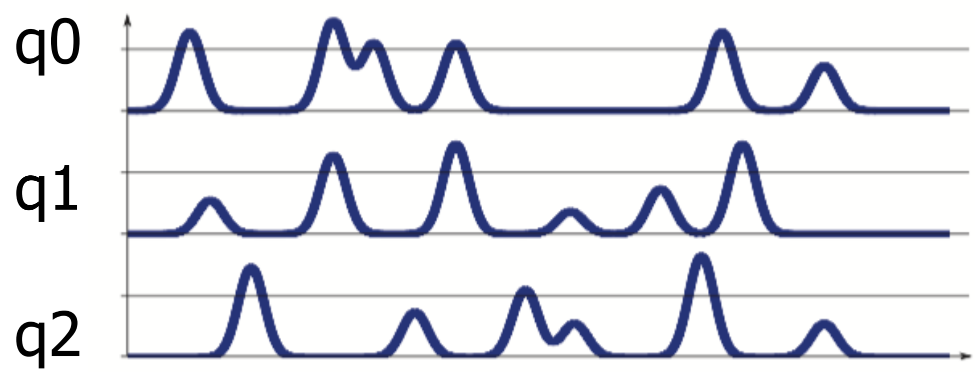


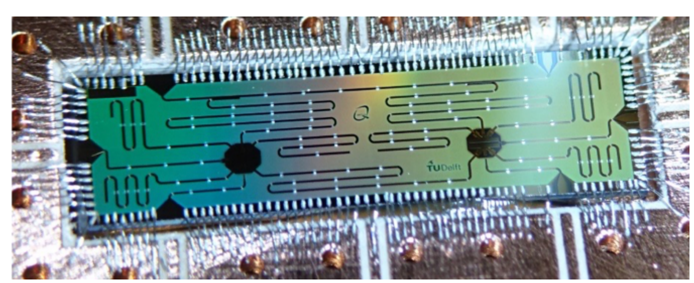
OpenQL (eQASM, cQASM) - TU Delft/Qutech
Quantum Development Kit (Q#) - Microsoft
Quiskit (OpenQASM, OpenPulse) – IBM
Forest (pyQuil,Quil) – Rigetti
ProjectQ (Python, OpenQASM) - ETH Zurich
Scaffold (ScafCC, QASM) – Chicago University

QASM-like instructions

```
qubit 3
H q0 | H q1
CNOT q1,q2
CNOT q0,q2
H q0 | H q1 | H q2
measure q0 | measure q1 | measure q2
```

Series of pulses





Full-stack implementation

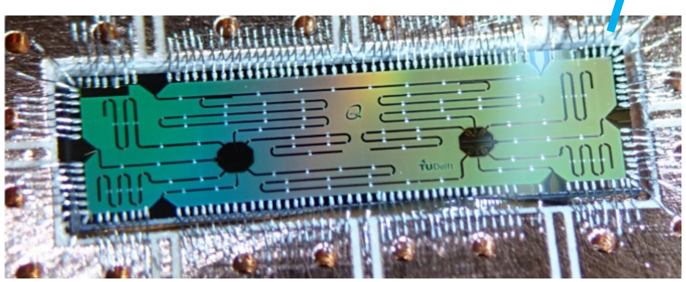
Ground floor

~300K

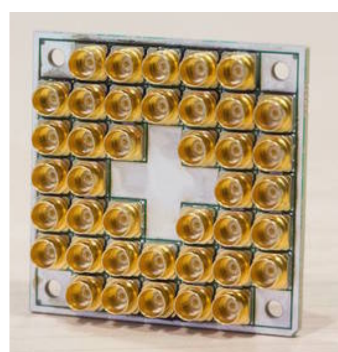
~70K

4K

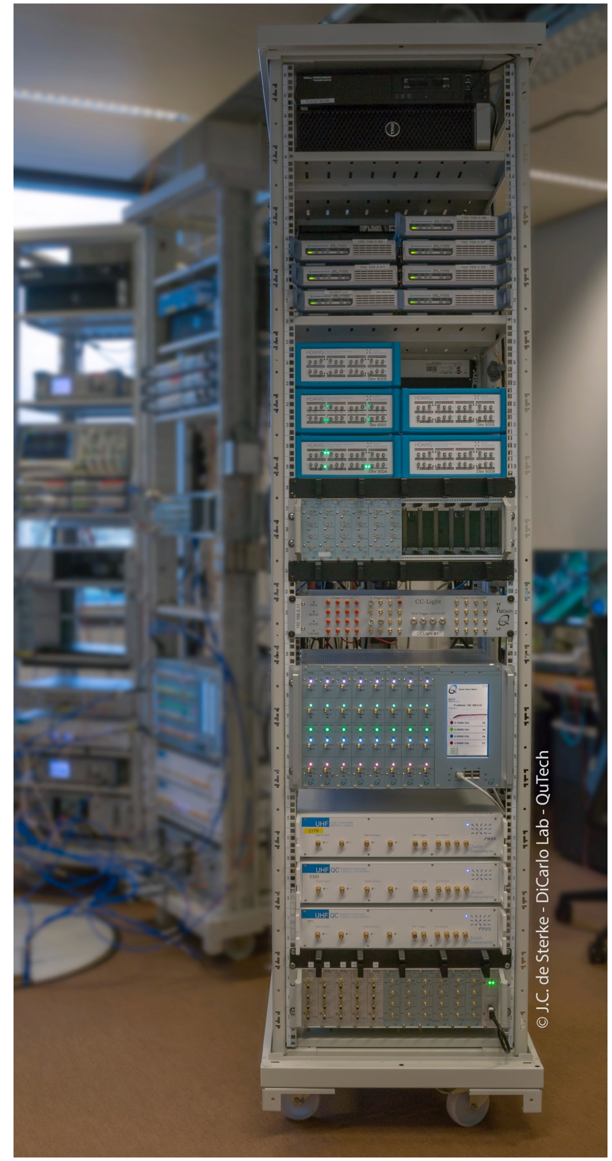
20mK



Superconducting quantum processor

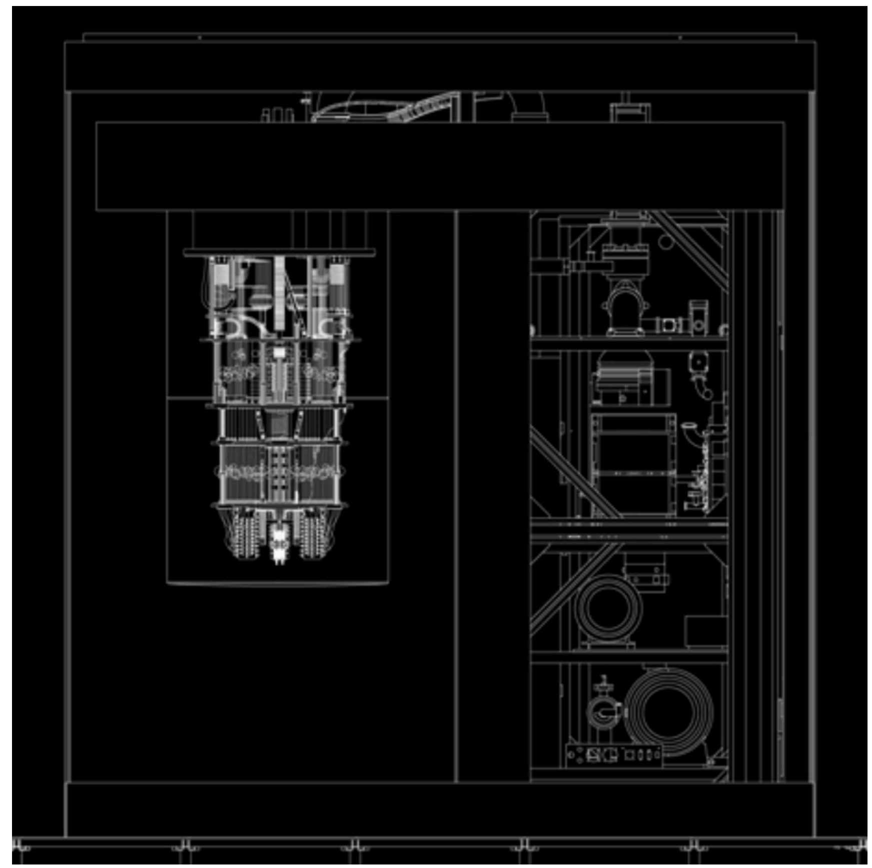


First floor



Full-stack implementation

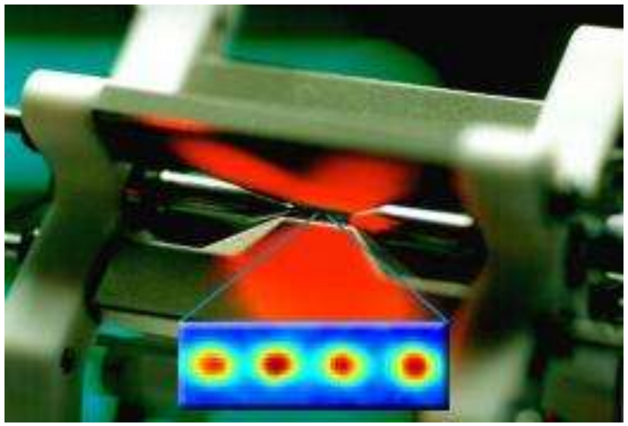
The IMB Q System One



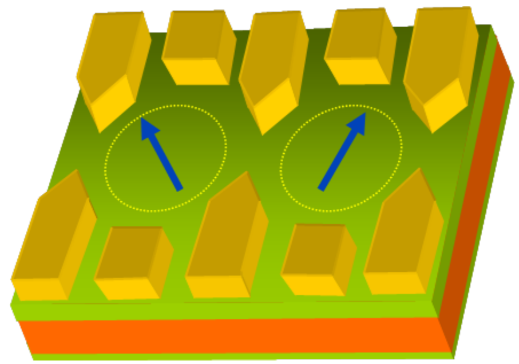
Quantum part (20 qubits, 100 microseconds) + classical part
2.7m tall, 2.7m wide

Challenge 1: Quantum devices

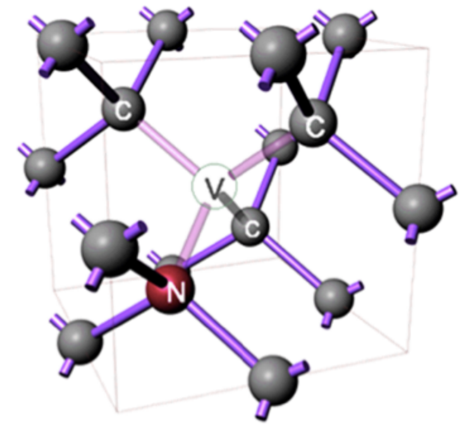
Trapped ions



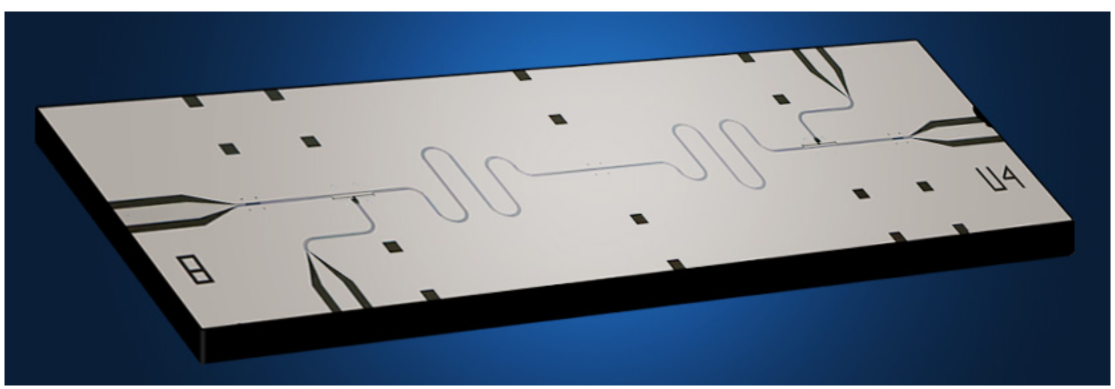
Quantum dots



NV centers



Superconducting qubits

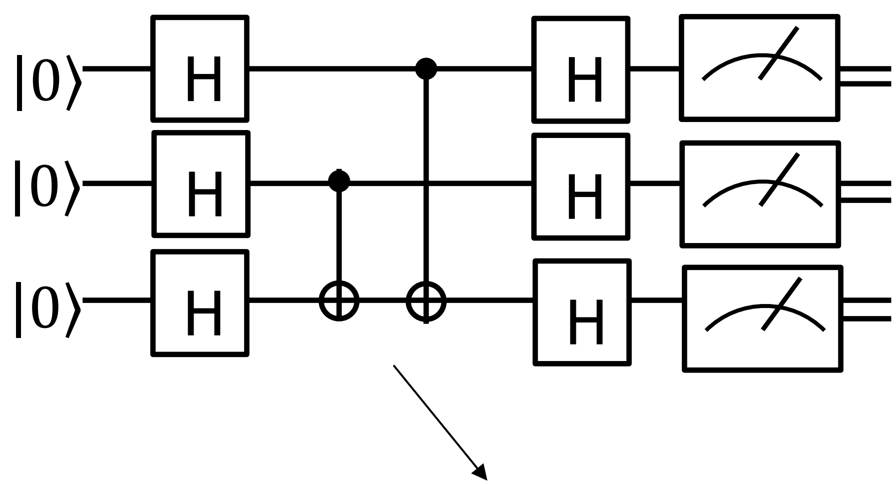


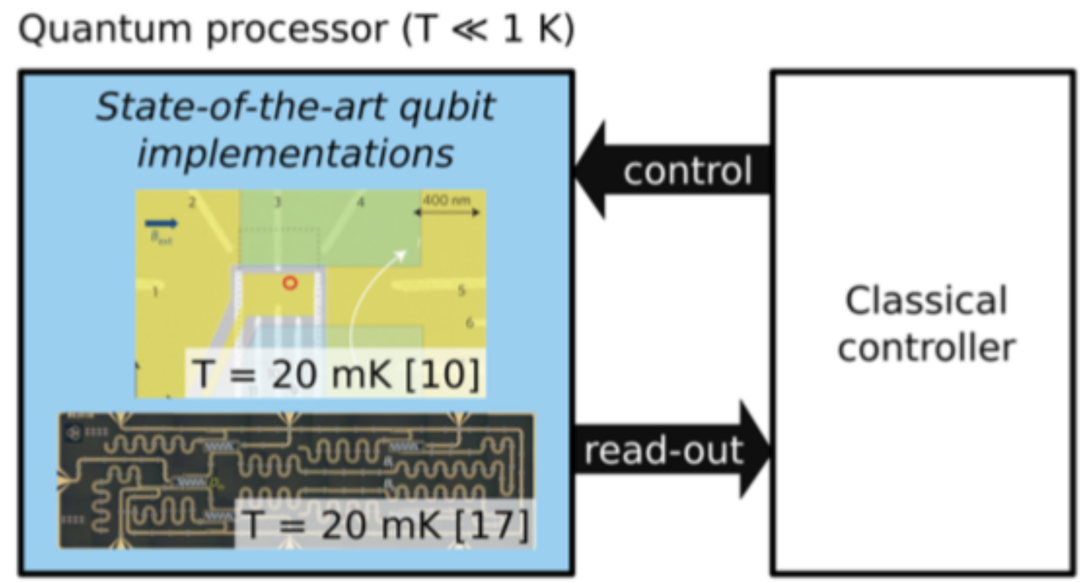
Majoranas

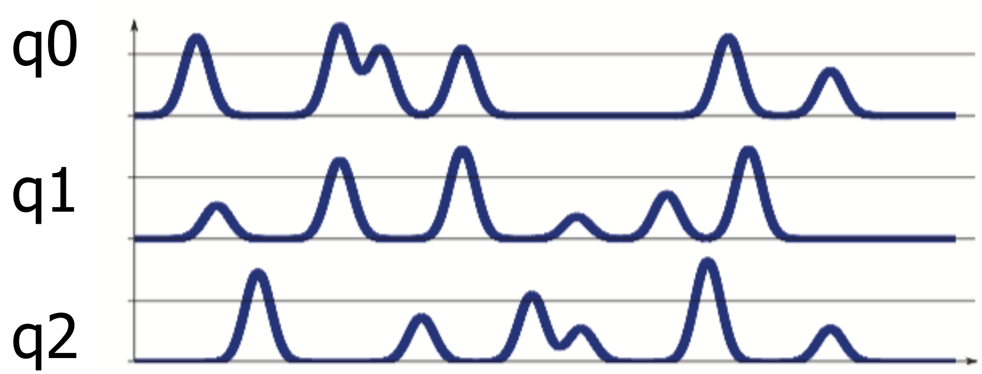
Enhancing coherence, operation fidelity and scalability

Challenge 2: Classical control electronics

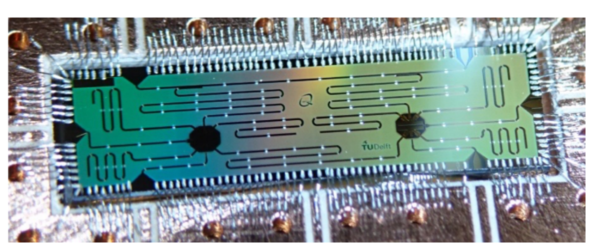
Scalable control system







F. Sebastiano et al., "Cryo-CMOS electronic control for scalable quantum computing", *DAC, 2017.*



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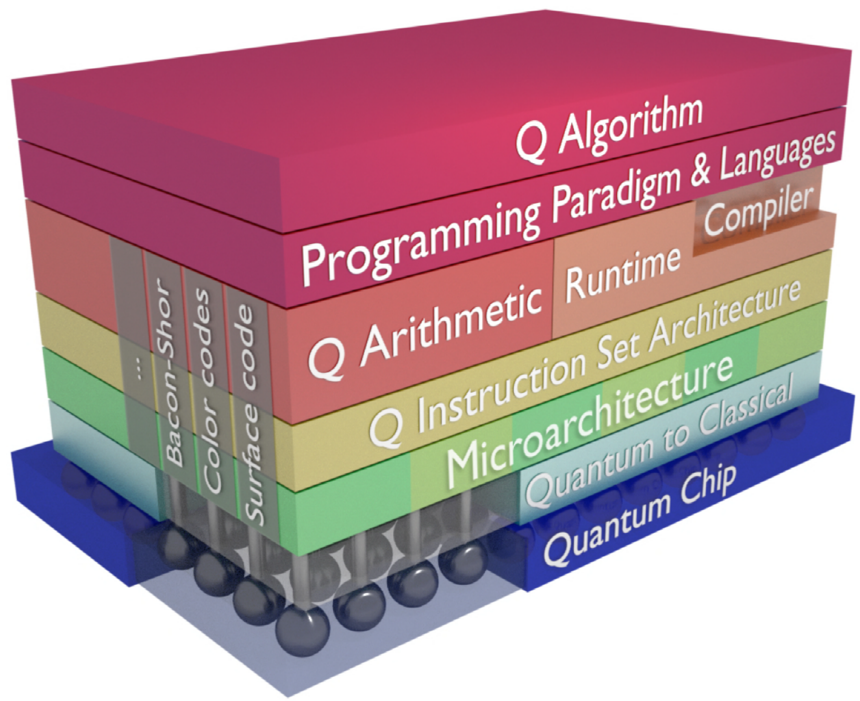
Challenge 3: SW-HW codesign

Programming languages, compilers, instruction set architecture and microarchitecture, hybrid classical-quantum computing paradigm, fault-tolerant quantum computation



C. G. Almudever et al. "The engineering challenges in quantum computing." *Design, Automation & Test in Europe Conference & Exhibition (DATE), 2017*.

S. Resch, and U R. Karpuzcu. "Quantum Computing: An Overview Across the System Stack." *arXiv preprint arXiv:1905.07240* (2019).

A.D. Córcoles et. al. ”Challenges and Opportunities of Near-Term Quantum Computing Systems." *arXiv preprint arXiv:1910.02894* (2019).

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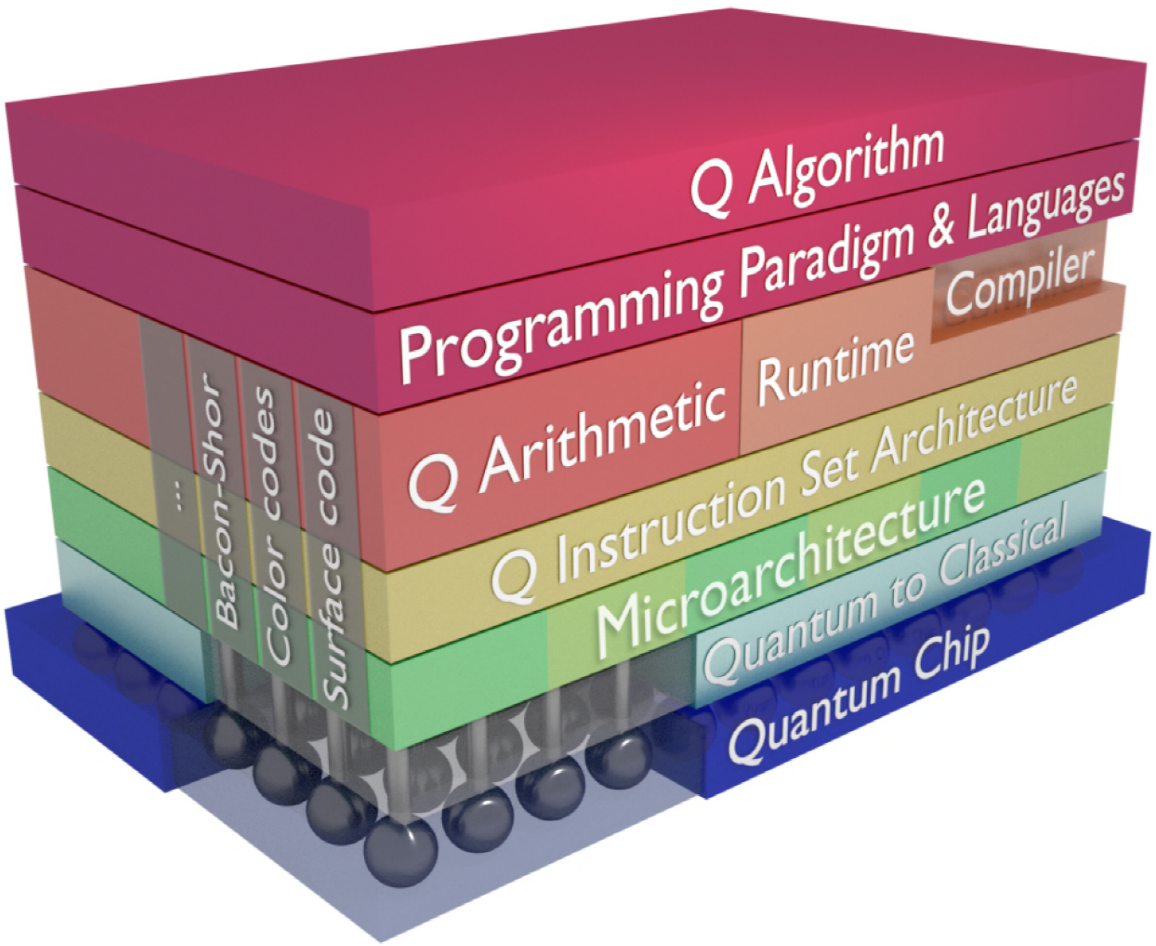
Architecting full-stack quantum systems

Full-stack quantum systems already exist



Carmen G Almudever, et al. “The engineering challenges in quantum computing”, DATE, 2017.

Quantum Architecting (QuArch) era

- To complete the system
- To improve the impairments of the quantum devices
- To allow the exploration of quantum applications

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Dealing with diversity and device impairments/constraints

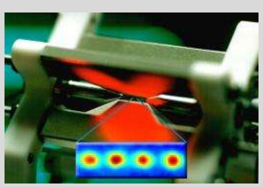
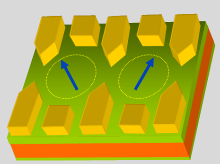
Software level

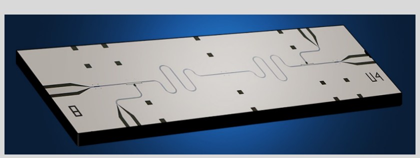
- OpenQL (eQASM,cQASM) - TU Delft/Qutech
- Quantum Development Kit (Q#) - Microsoft
- Quiskit (OpenQASM, OPenPulse) – IBM
- Forest (pyQuil,Quil) – Rigetti
- ProjectQ (Python, OpenQASM) - ETH Zurich
- Scaffold (ScafCC,QASM) – Chicago University
- Tket – Cambridge Quantum Computing

Physical-aware software

- Optimization
- Gate decomposition
- Scheduling
- Mapping

Physical level



- Short coherence time
- High gate error rates
- Resource-constrained devices

Quantum computers in the cloud