Introduction to Quantum Computing Hardware

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Outline

1. Basics about quantum computers

- 2. Comparison of different quantum computing hardware platforms:
 - Trapped ions
 - Neutral atoms
 - Superconducting qubits
 - Photonics



Why quantum computers?

- Quantum computing (QC) promises major speedups for *certain* problems
- Accelerators for classical computers
- Built from *quantum bits* (qubits) = microscopic two-level systems
 - \rightarrow Fundamentally different computing architecture and software

Use properties of quantum systems for computations

- Superposition $|0\rangle + |1\rangle$
- Entanglement of multiple qubits
- Information encoding: a system with N qubits can be in 2^N different states simultaneously

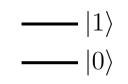
 $A\cdot |00\rangle + B\cdot |01\rangle + C\cdot |10\rangle + D\cdot |11\rangle$

Classical: 4 bits

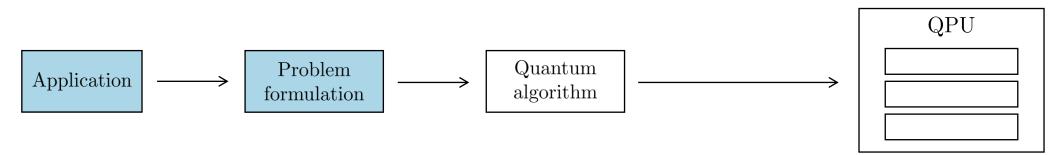
QC: 2 qubits

Example: Penicillin

~10⁸⁶ classical bits vs. 286 qubits



Solving problems on quantum computers



Map problem variables to qubits

- Assignment of production jobs
- Occupation of electronics orbitals
- Nodes of a graph

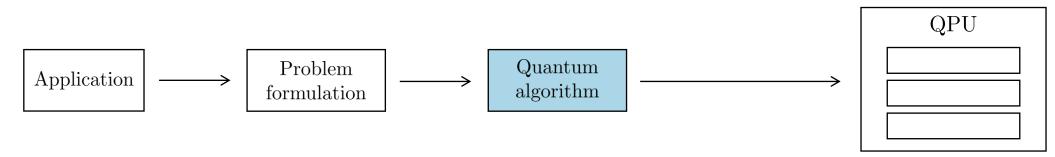
 $|q_1\rangle - |q_2\rangle - |q_3\rangle - |q_4\rangle - |q_5\rangle - |q_6\rangle - |q_7\rangle - |q_8\rangle - |q_8$

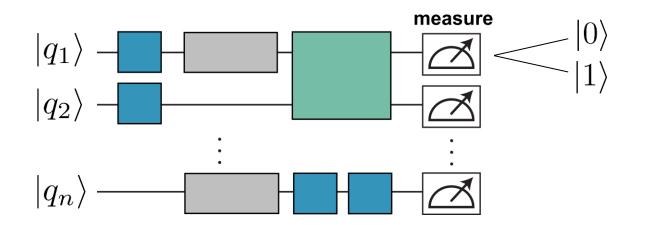


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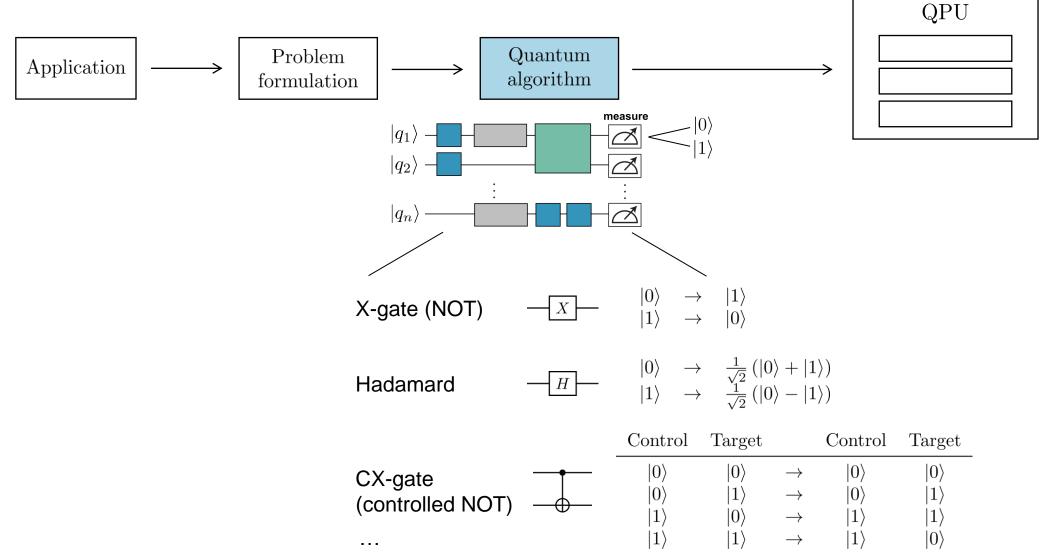
Solving problems on quantum computers



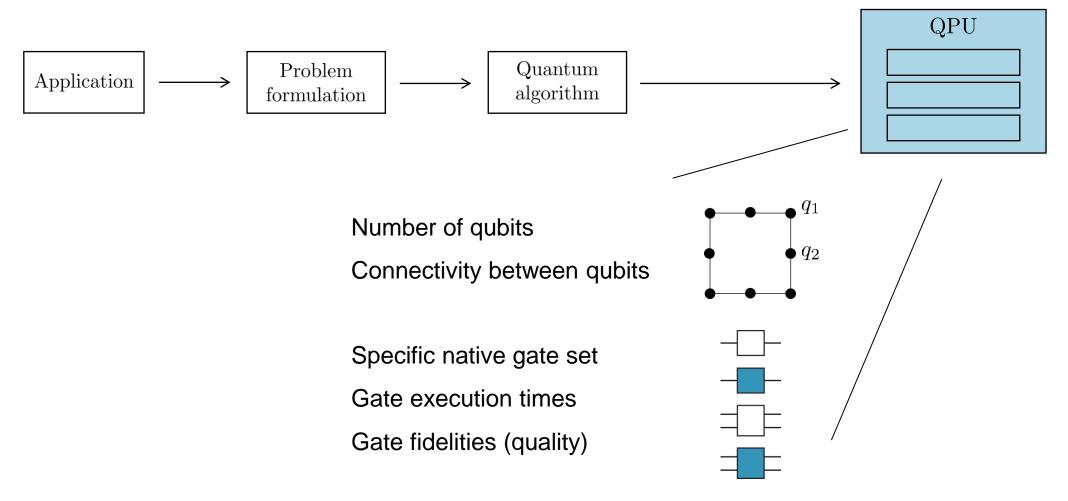




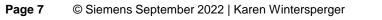
Solving problems on quantum computers



Properties of Quantum Processing Units (QPUs)

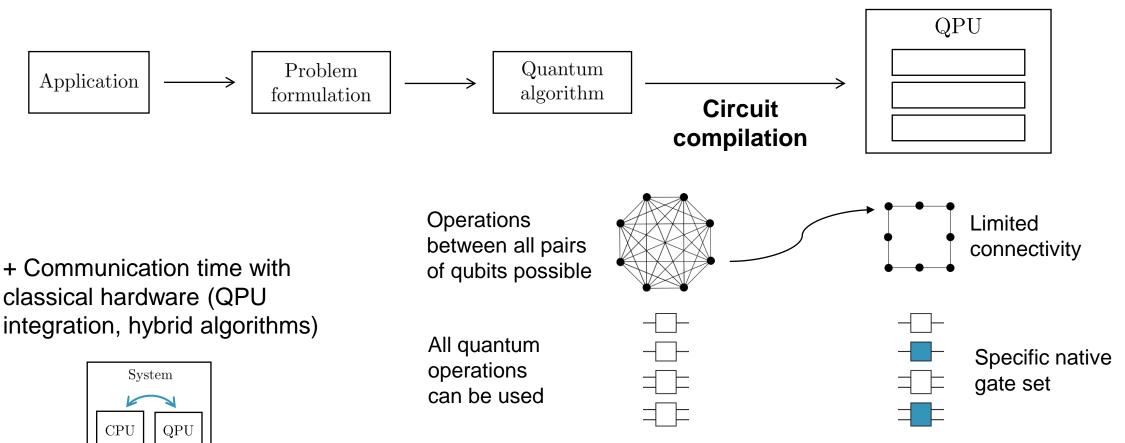


Coherence time





QPU properties influence performance of algorithms



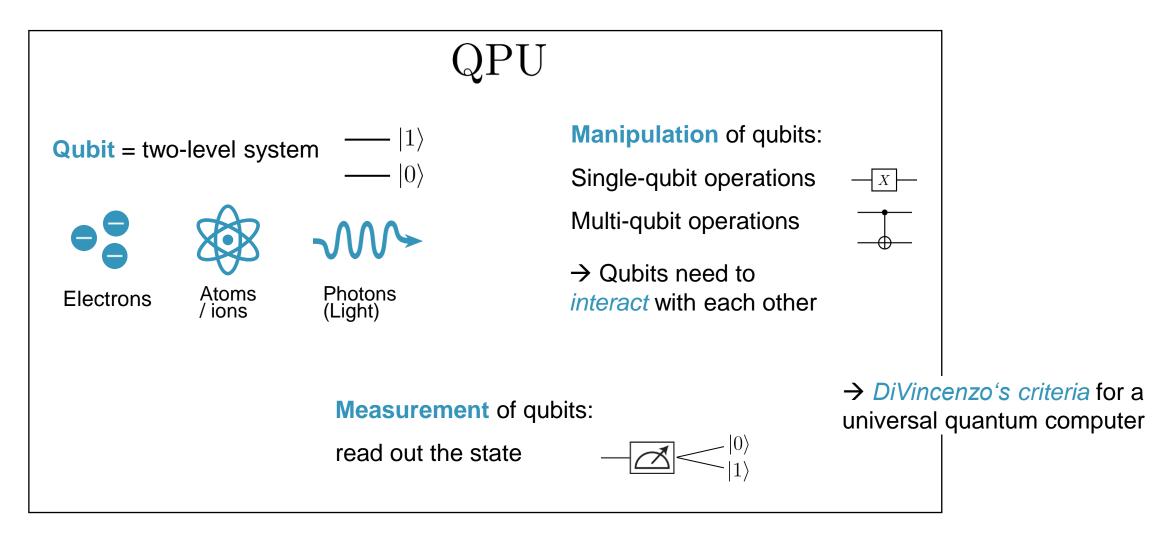
 \rightarrow Longer circuits: more noise & increased runtime

Co-design: adapt QC software and hardware to a specific application

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Implementation of QPUs





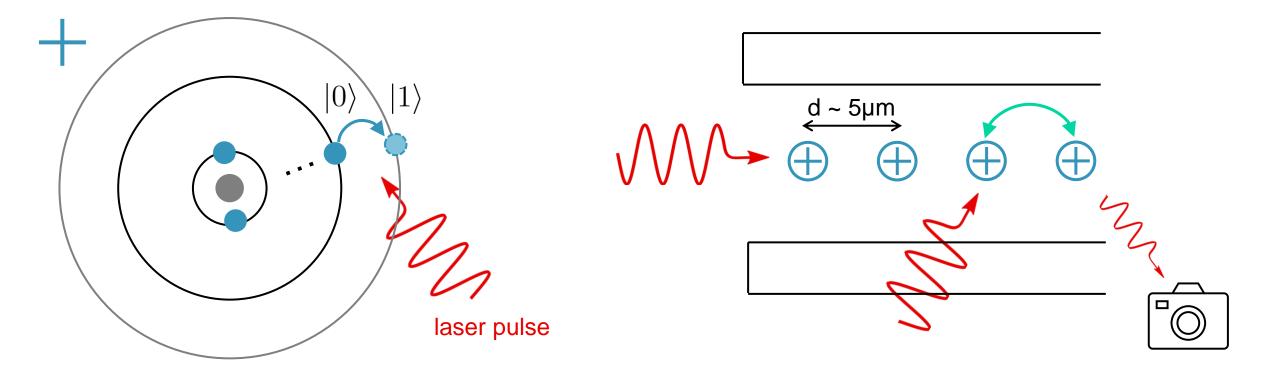




Qubits = Single ions

Trapping and manipulation of ions

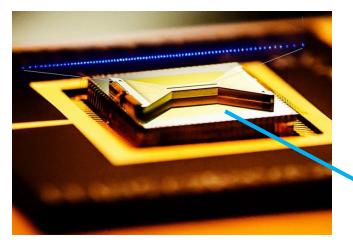
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Trapped ions

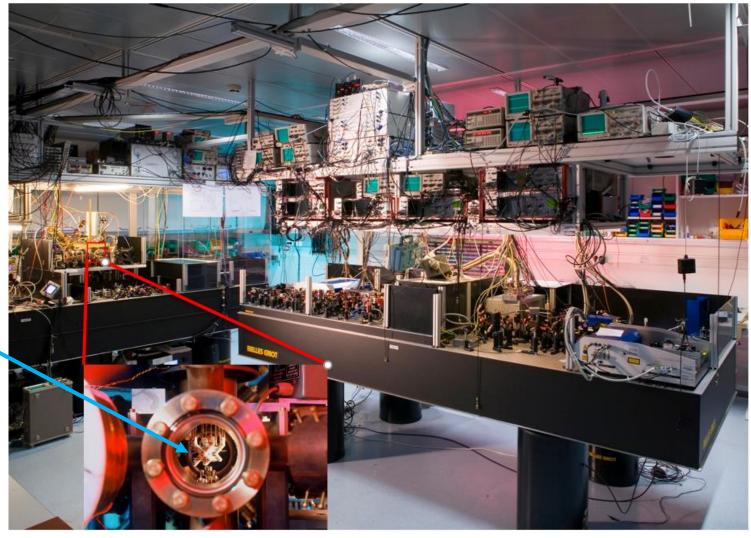




https://physicsworld.com/a/ion-basedcommercial-quantum-computer-is-a-first/

Key players:





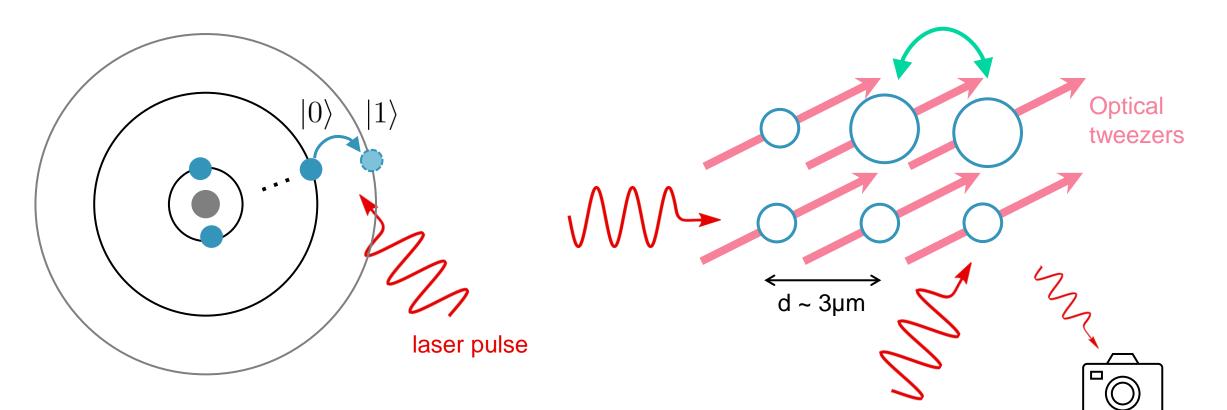
https://thequantumaviary.blogspot.com/2021/03/heres-how-ion-trap-quantum-computers.html

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Qubits = Single *neutral* atoms

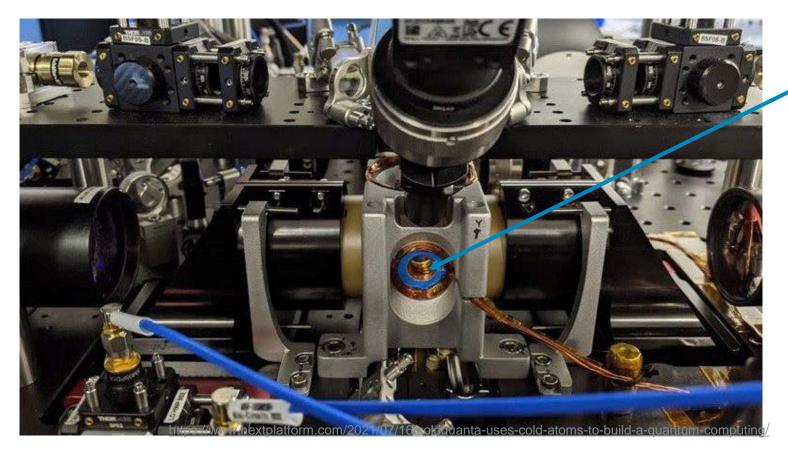
Trapping and manipulation of atoms

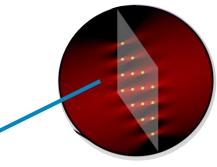




Neutral atoms







https://quantum-journal.org/papers/q-2020-09-21-327/pdf/

Key players:





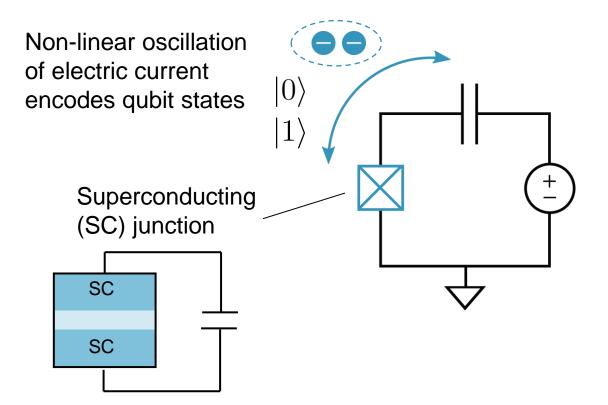




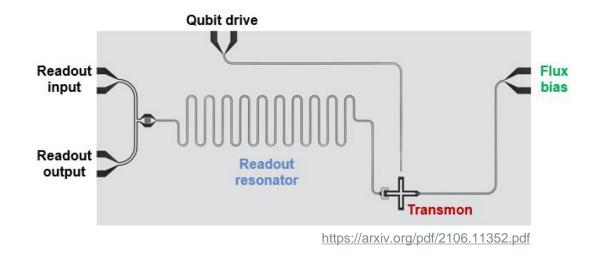




Qubits = Electronic circuits



Manipulation and read-out with microwaces

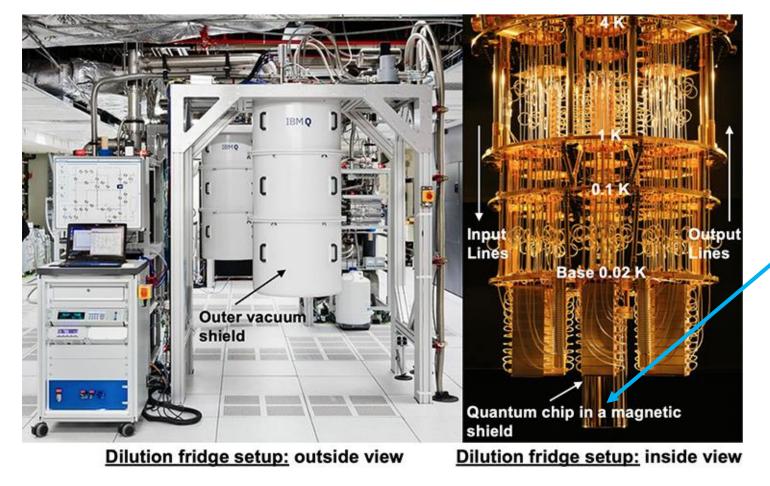


Interaction by physical wiring

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Superconducting qubits

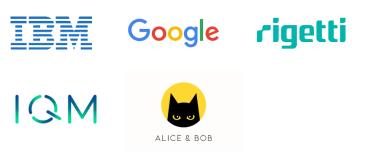


https://www.ibm.com/blogs/research/2020/01/quantum-limited-amplifiers/



https://miro.medium.com/max/1400/0*2xf3QTMAHWz19Hpn

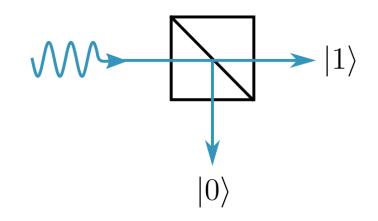
Key players:







Qubits = Photons



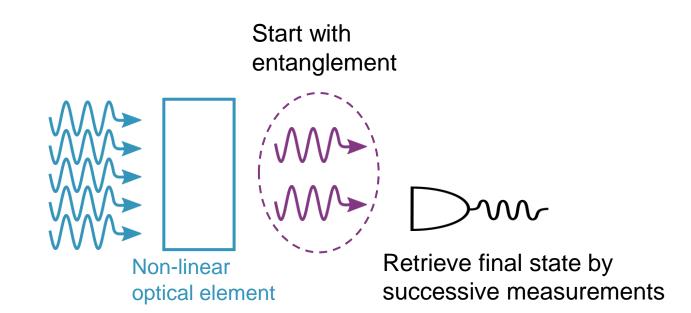
Single-qubit manipulations:

- Beam splitters
- Phase shifters
- Delay lines

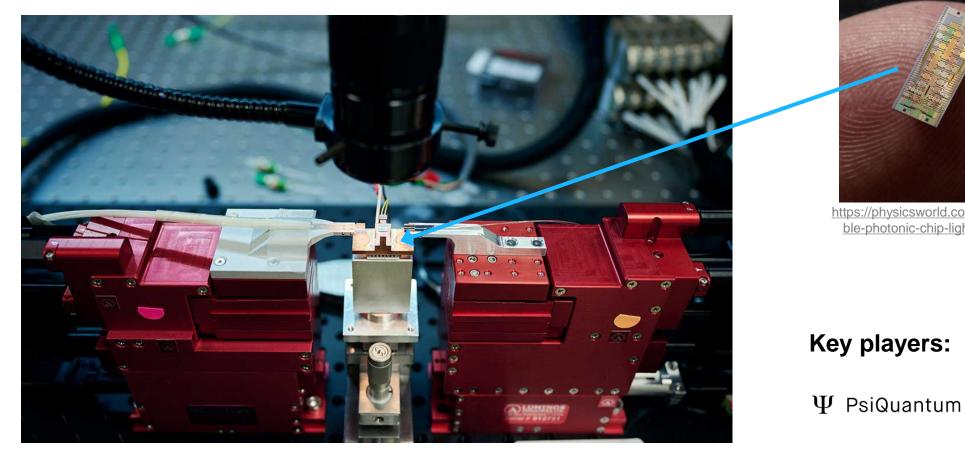


Multi-qubit operations are difficult

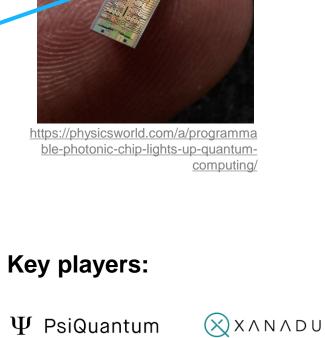
→ Measurement-based quantum computing



Photonics VV



https://www.i-micronews.com/first-photonic-quantum-computer-on-the-cloud/?cn-reloaded=1



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All platforms have advantages and disadvantages

| Platform | # Qubits | Scalability | Gate fidelities | Qubit Connectivity | Gate times | Special features |
|------------------|----------|-------------|--------------------|-----------------------|------------|--|
| SC qubits | ~ 100 | + | ++ | - | +++ | Standard fabrication techniques, flexibility |
| Trapped lons | ~ 20 | - | ++ | +++ | ++ | Natural implementation of > 2-qubit gates |
| Neutral atoms | ~ 100 | ++ | - | ++ | ++ | Operation at room temperature, > 2 qubit-gates |
| Photonics | ? | +++ | | | | Standard fabrication techniques, (operation at room temperature) |

 \rightarrow Different QPU-types might be used for different applications



There is more

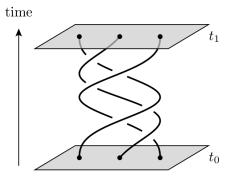


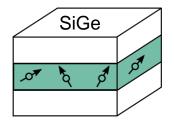
NV centers in diamond

 \rightarrow Operation at room temperature

Topological qubits (Microsoft)

 \rightarrow Resistant against noise



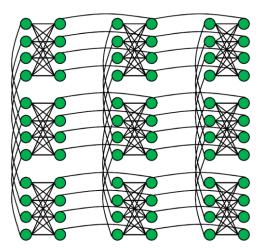


Quantum dots

 \rightarrow Silicon-based

Quantum annealers

- \rightarrow Many qubits available
- \rightarrow Limited in applications



https://www.nature.com/articles/s41598-018-38388-4

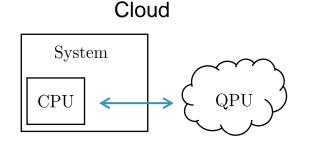


Current status and outlook

Today:

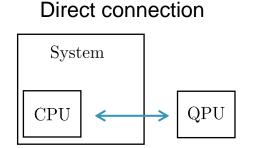
NISQ (Noisy Intermediate-Scale Quantum)

- devices
 - Limited number of qubits (~100) and quantum operations
 - > Subject to noise
 - > Limited coherence time

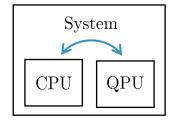


Near- to midterm:

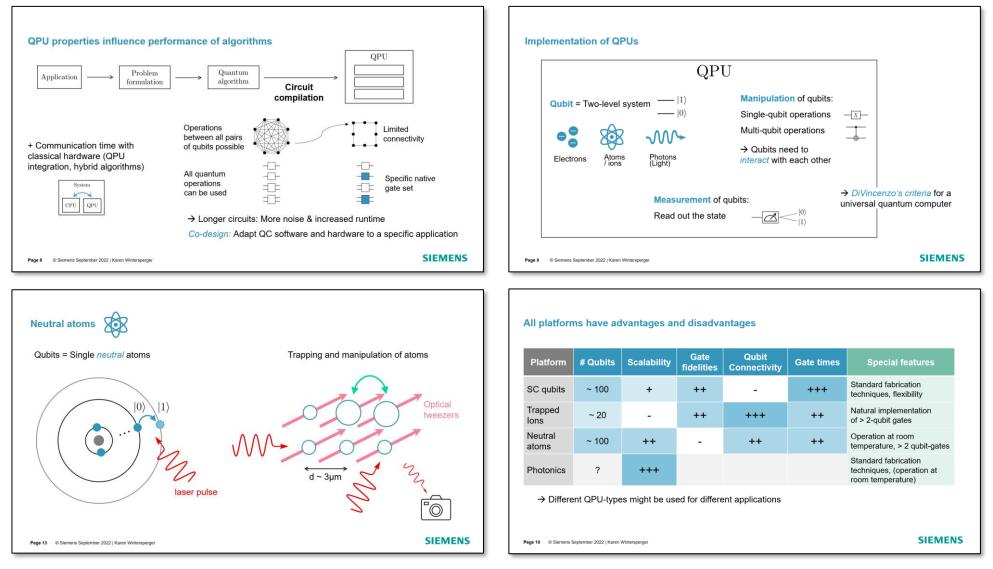
- Improve hardware: up to ~10.000 qubits announced in 2-3 years (Photonics: 1 Mio)
- > Error mitigation / error correcting codes
- Application-oriented design of QPU and algorithms
- > Improve deployment:



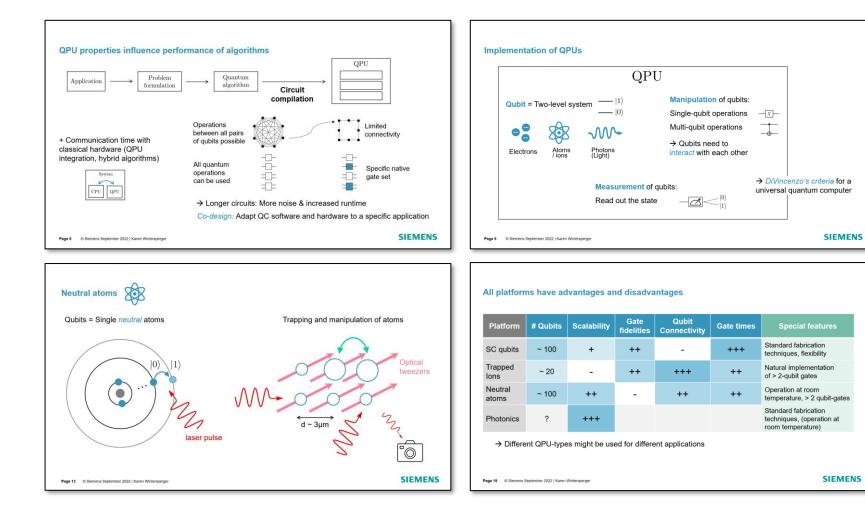
Integrated system



Summary



Thank you!



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