QUANTUM COMPUTING - BASICS

11.09.2019 | LOTTE GECK

Member of the Helmholtz Association

JÜLICH Forschungszentrum

CRYOGENIC INTEGRATED CIRCUITS

Recap

Goal

- Design, implement and test <u>scalable</u> control and readout electronics for quantum computers

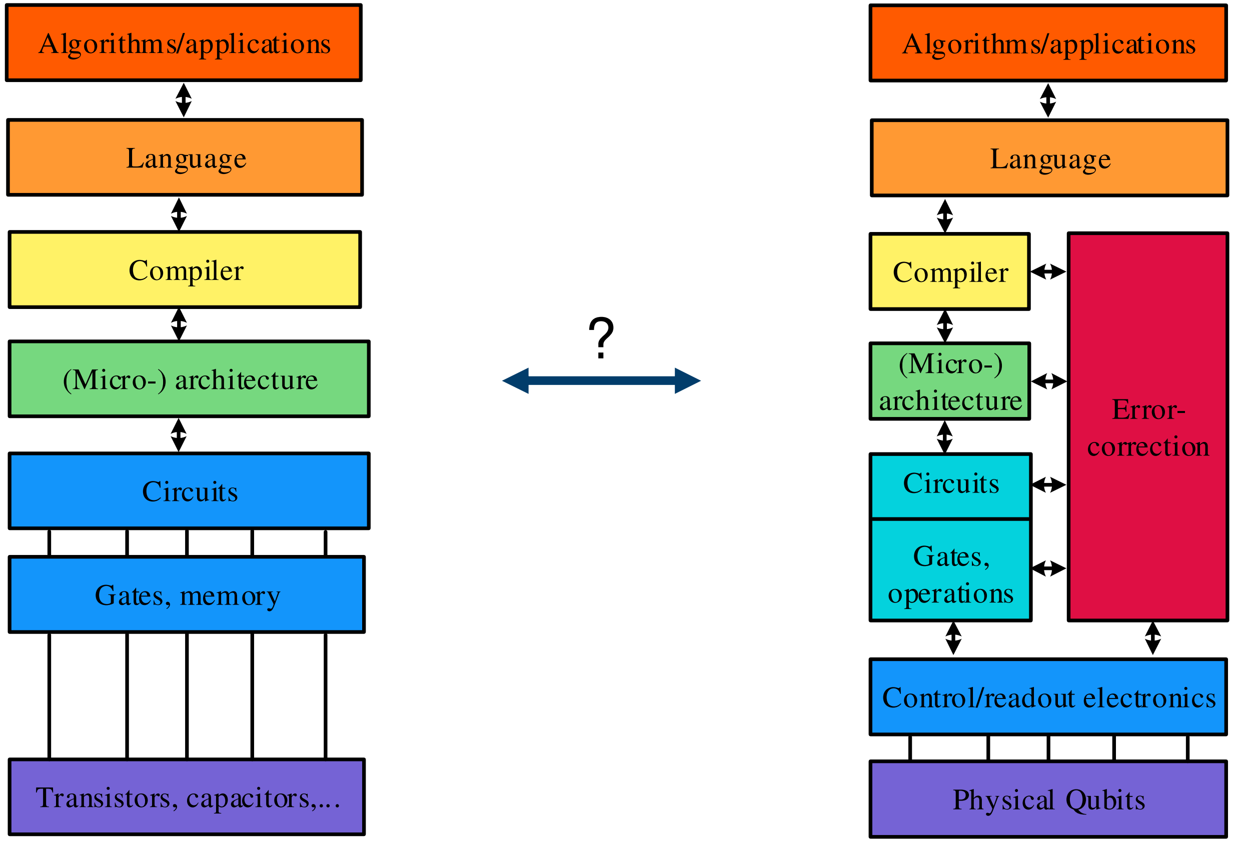
Challenges

- Scalability: operate thousands and millions of qubits in parallel
- Cryogenic environment with very limited cooling power (few mW in total at < 100mK)
- Area restrictions for 1:1 coupling of electronics with qubits
- Interface to room temperature electronics

➡ **Only possible with highly integrated cryogenic electronics**

oxford-instruments.com

CLASSICAL VS QUANTUM COMPUTER



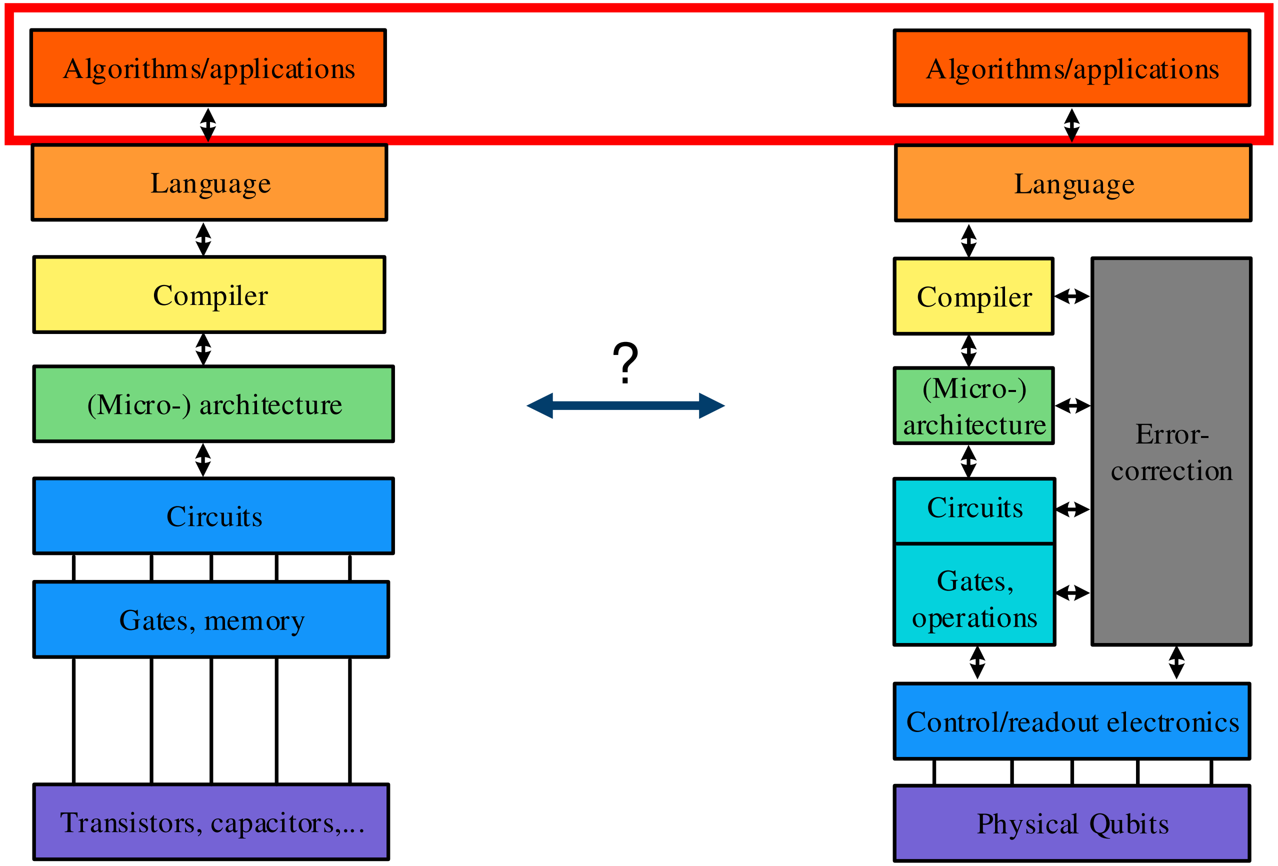
Mathematicians

Computer Scientists

Physicists

Electrical Engineers

CLASSICAL VS QUANTUM COMPUTER



QC VS CLASSICAL C

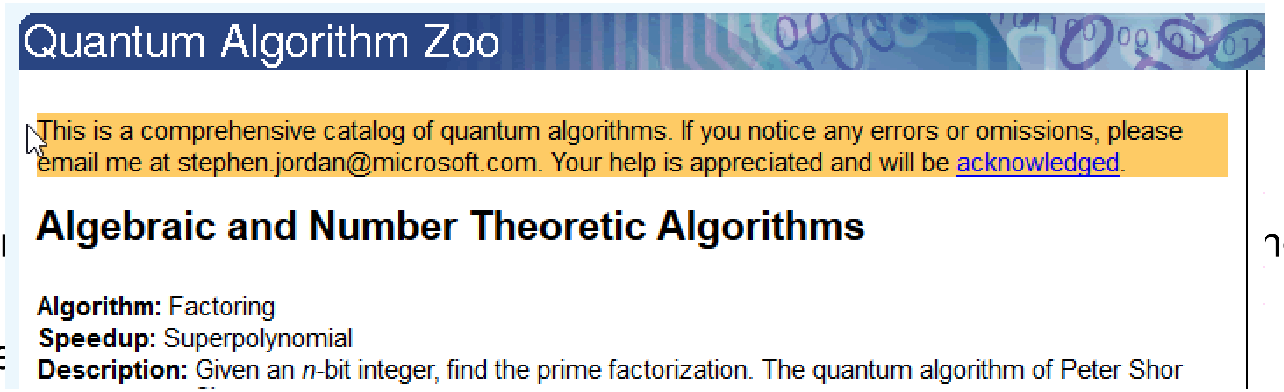
Algorithms

Classical Computer

- Can run classical algorithms

Quantum Computer

- Can run classical and quantum algorithms



Most efficient algorithı

ıor‘s algorithm

Run time: sub-expone

➔Factoring a 2048 bit number takes 100 years on a super computer

~ 50 algorithms

quantumalgorithmzoo.org

➔ Factoring a 2048 bit number takes 26.7 hours

[1]

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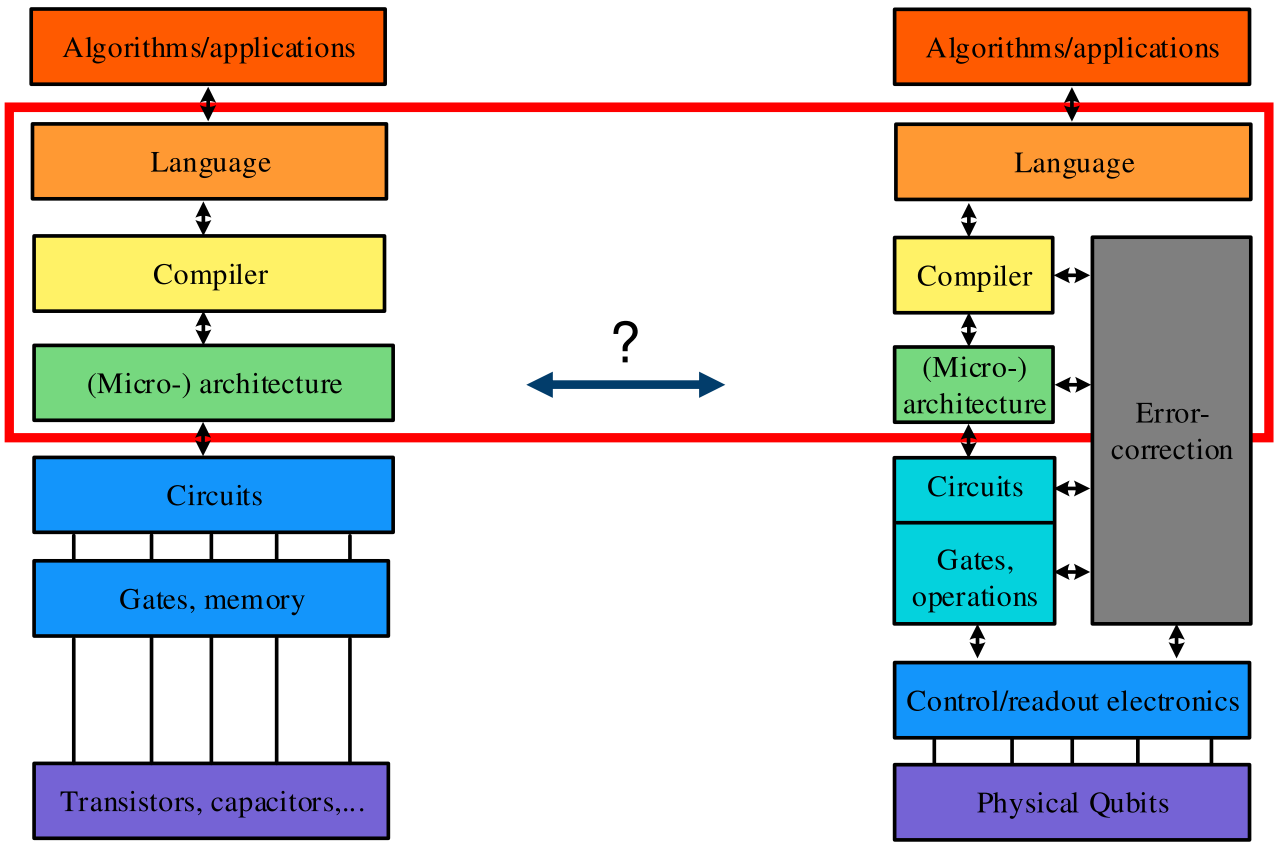
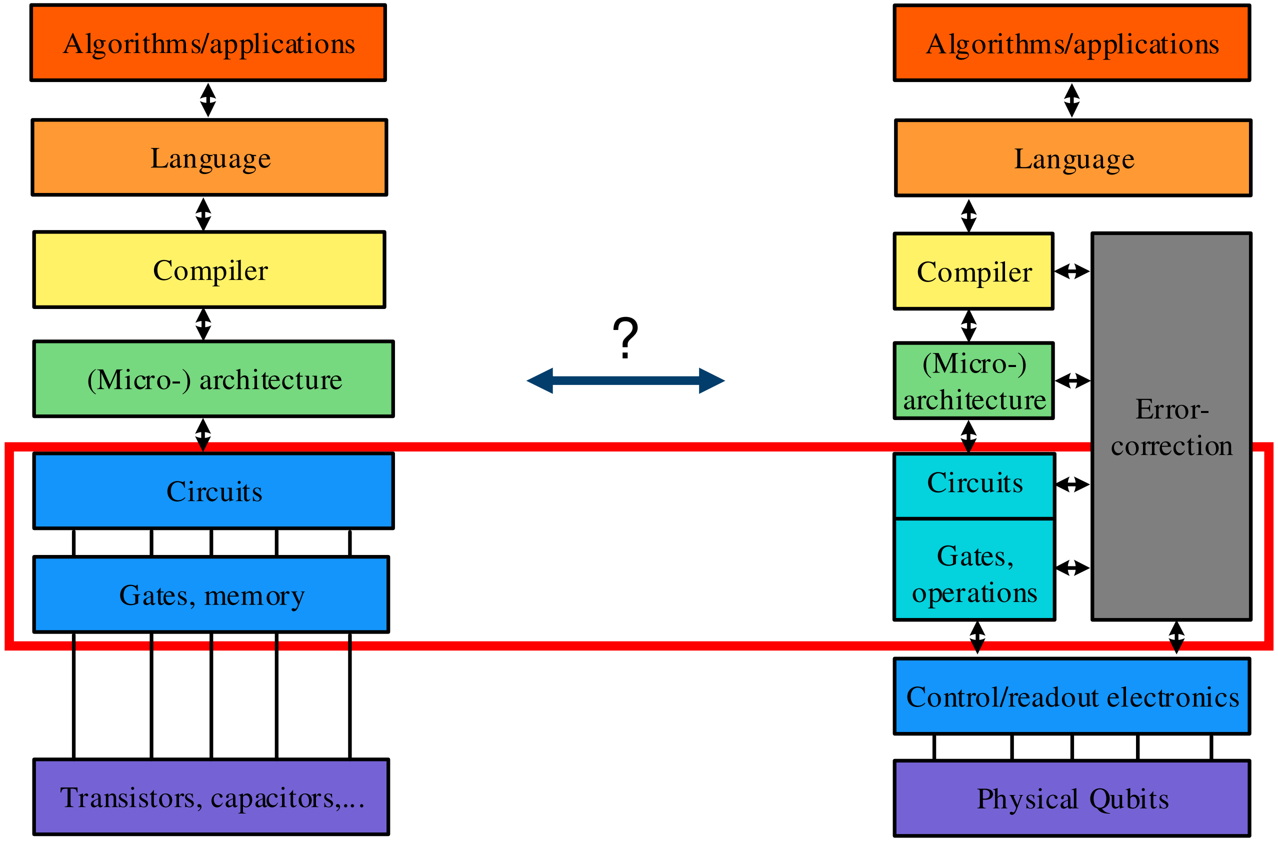
CLASSICAL VS QUANTUM COMPUTER



Programming Languages, Compiler, Software, Microarchitecture

- Languages:
  - QCL, Quantum pseudocode, Q#, Qlanguage, OpenQL,…
- Instruction sets:
  - Quil, OpenQASM, QUISA,…
- Software development kits:
  - ProjectQ, Quiskit, Forest, Quantum Developmet Kit, Cirq,…

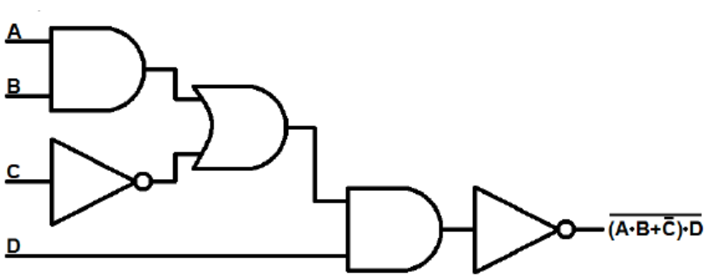
CLASSICAL VS QUANTUM COMPUTER



QC VS CLASSICAL C

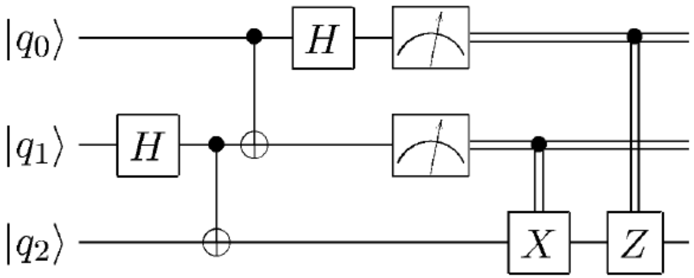
Circuits, Gates, Memory

Classical Computer



Irreversible and deterministic

Quantum Computer



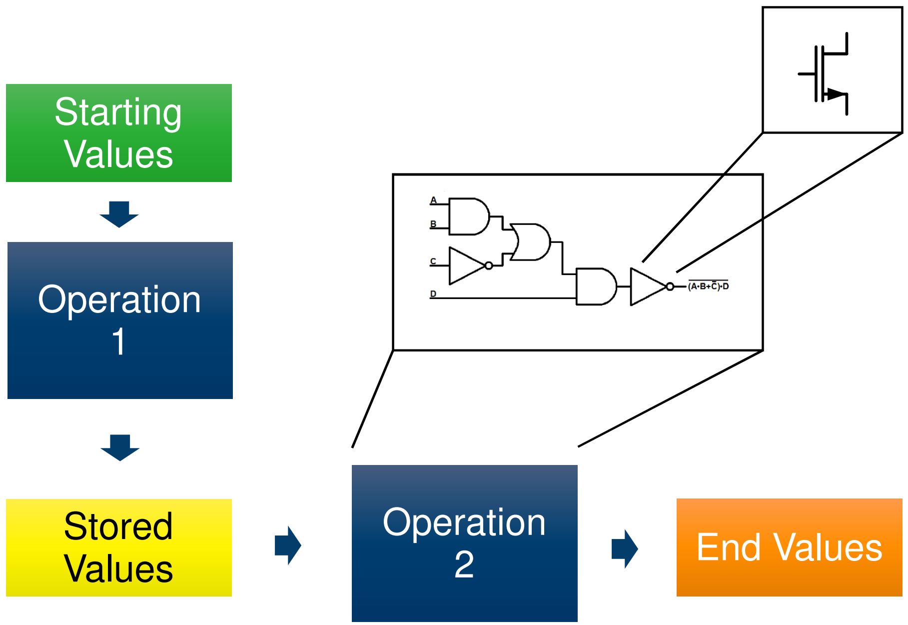
Reversible and non-deterministic

[1]

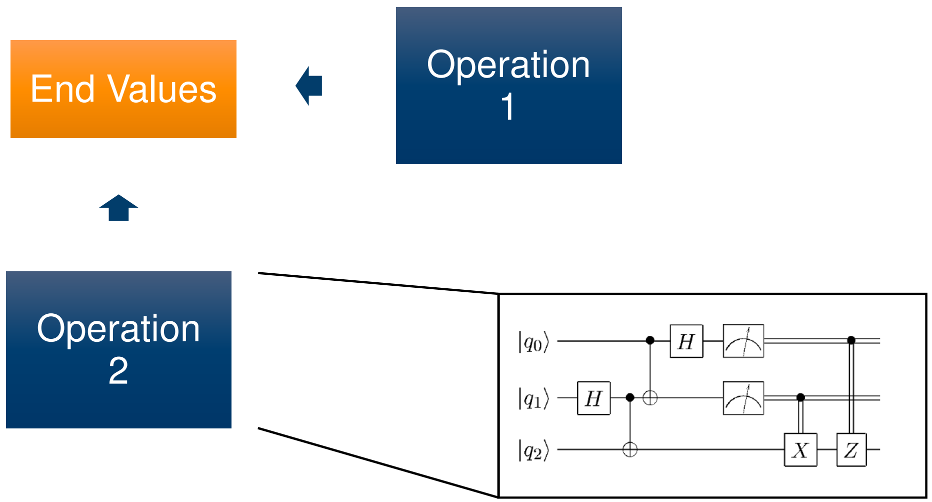
CLASSICAL VS QUANTUM COMPUTER

Circuit Execution

Classical Computer



Quantum Computer



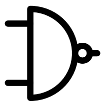
[1]

CLASSICAL VS QUANTUM COMPUTER

Gates

Classical Computer

- Universal gate: NAND



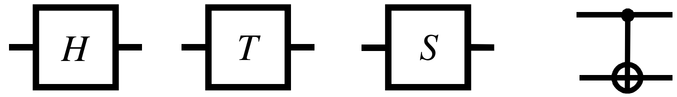
- Logical operation
- Truth tables

a	0	0	1	1
b	0	1	0	1
out	1	1	1	0

- Mostly one directional

Quantum Computer

- Universal gate set: {H,T,S,CNOT}



- Unitary operation
- Unitary matrix

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix} \quad \begin{bmatrix}1 & 0\\ 0 & e^{i\pi/4}\end{bmatrix} \quad \begin{bmatrix}1 & 0\\ 0 & i\end{bmatrix} \quad \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$$

- Reversible

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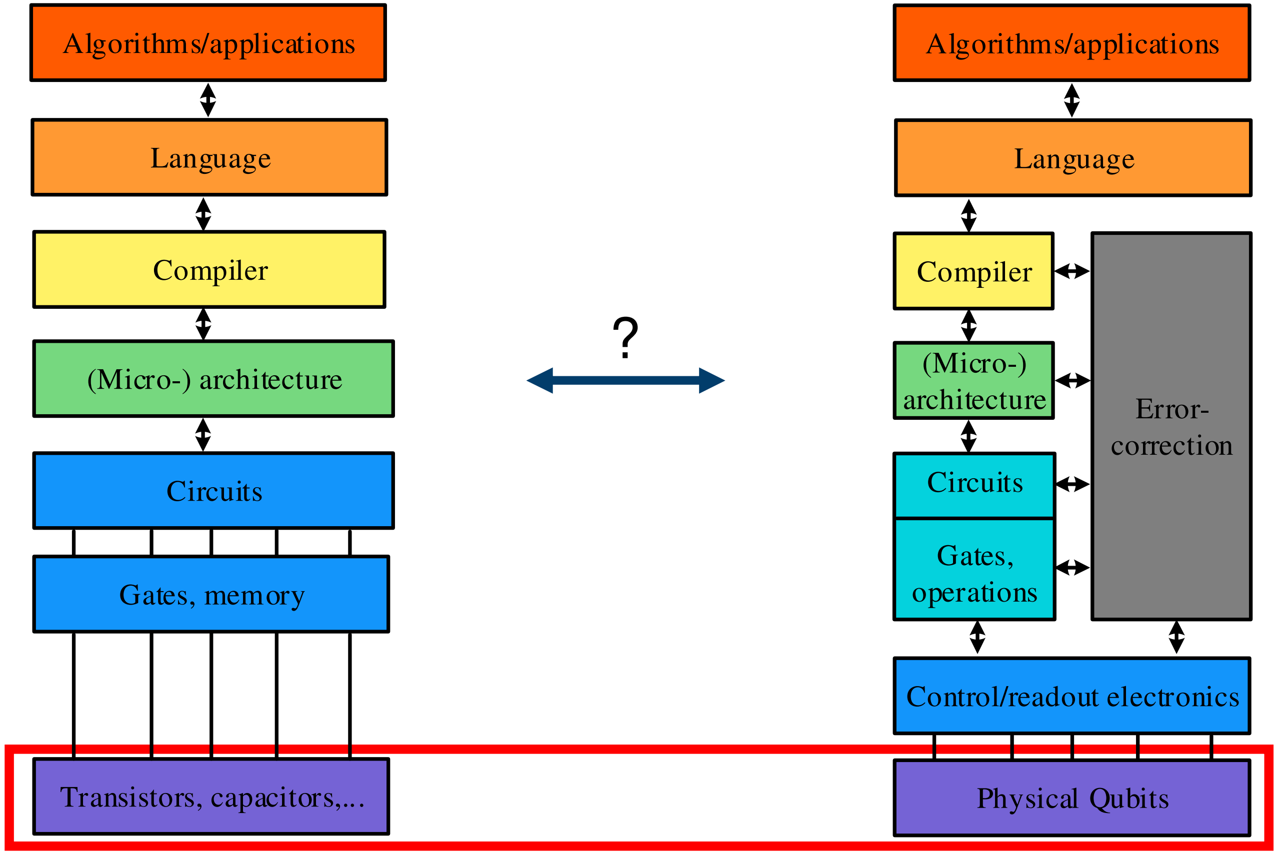
CLASSICAL VS QUANTUM COMPUTER



BASIC QUANTUM INFORMATION

The qubit

Term „Qubit“:

Used as basic unit of quantum information → „state of the qubit“

and

the technical realisation containing that information → qubit

State of a qubit: a two level quantum mechanical system

$$|\Psi\rangle = a\,|0\rangle + \mathrm{b}\,|1\rangle$$

$$\Leftrightarrow\ \vec{\Psi} = a \cdot \vec{e_1} + b \cdot \vec{e_2}$$

Superposition

$$|a|^2 + |b|^2 = 1 \ \text{ with } a, b \in \mathbb{C}$$

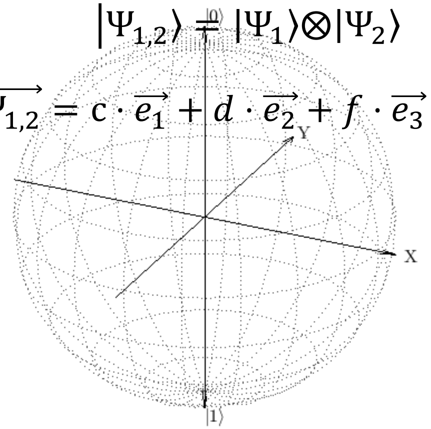
State readout: 0 or 1 with $|a|^2$ and $|b|^2$ probability

State of multiple qubits

Makes the state space bigger, e.g. 2qubits

$$|\Psi_{1,2}\rangle = |\Psi_1\rangle \otimes |\Psi_2\rangle$$

$$\Leftrightarrow \overrightarrow{\Psi_{1,2}} = \mathrm{c} \cdot \vec{e_1} + d \cdot \vec{e_2} + f \cdot \vec{e_3} + g \cdot \vec{e_4}$$



BASIC QUANTUM INFORMATION

Changing states and doing gates

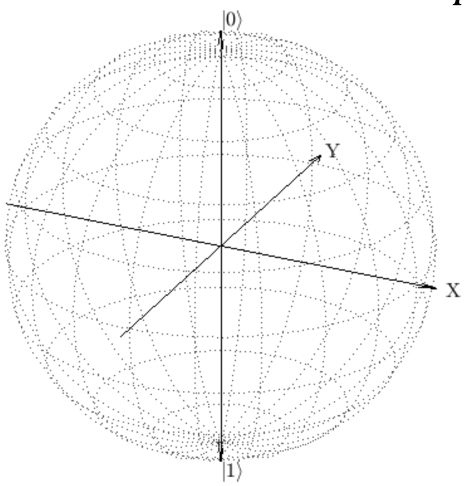
Single qubit gate = rotations in Bloch sphere

➔Multiplication with unitary matrix

$$|\Psi\rangle = U \cdot |\Psi_0\rangle$$

➔Rotation matrix e.g.:

$$R_x(\pi) = \begin{bmatrix} 0 & -i \\ -i & 0 \end{bmatrix}$$



Multiple qubit gate:

➔ Multiplication with unitary matrix

$$\text{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

➔ Example:

$$|\Psi_{1,2}\rangle = \text{CNOT} \cdot |\Psi_{0(1,2)}\rangle$$

➔ But:

$$|\Psi_{1,2}\rangle \neq |\Psi_1\rangle \otimes |\Psi_2\rangle$$ Entanglement

BASIC QUANTUM INFORMATION

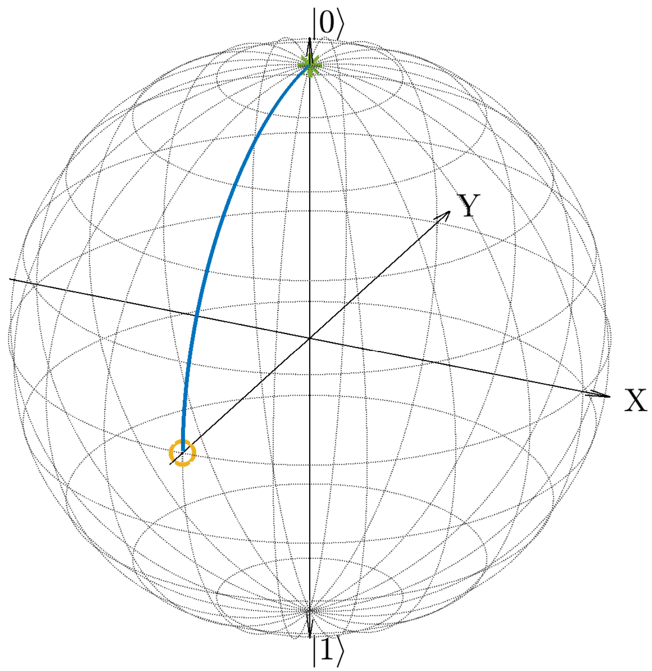
Exercise 1

How to get from * to o ?

$$R_x(\theta) \equiv e^{-i\frac{\theta}{2}X} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}X = \begin{bmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$R_y(\theta) \equiv e^{-i\frac{\theta}{2}Y} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}Y = \begin{bmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$R_z(\theta) \equiv e^{-i\frac{\theta}{2}Z} = \cos\frac{\theta}{2}I - i\sin\frac{\theta}{2}Z = \begin{bmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{bmatrix}$$



BASIC QUANTUM INFORMATION

Exercise 2

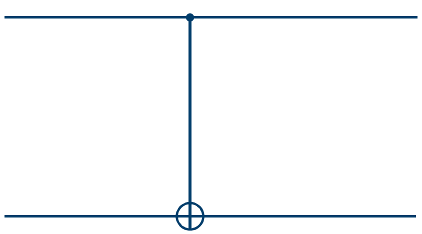
What quantum circuit is this and what is the output?

Help:

$$|A\rangle \otimes |B\rangle = \begin{bmatrix} A_{11}B & A_{12}B \\ A_{21}B & A_{22}B \end{bmatrix}$$

$|\Psi_{0,1}\rangle = \alpha|0\rangle + \beta|1\rangle$

$|\Psi_{0,2}\rangle = 1 \cdot |0\rangle + 0 \cdot |1\rangle$



$|\Psi_{1,2}\rangle = ?$

input

output

BASIC QUANTUM INFORMATION

Quality of gates

How do we determine the gate quality?

➔Calculate the fidelity (0,1):

$$F = \frac{1}{n^2} \left| \mathrm{Tr}[U^{\mathrm{T}}{}_{\mathrm{ideal}} \cdot U] \right|^2$$

➔Benchmark set by error correction (infidelity):

$$1 - F = 10^{-2} - 10^{-3}$$

(current research^best between $10^{-1} - 10^{-2}$)

BASIC QUANTUM COMPUTING

Qubit implementations

Trapped Ions

Semiconductor Qubits

Superconducting Qubits

BASIC QUANTUM COMPUTING

GaAs qubit

Build:

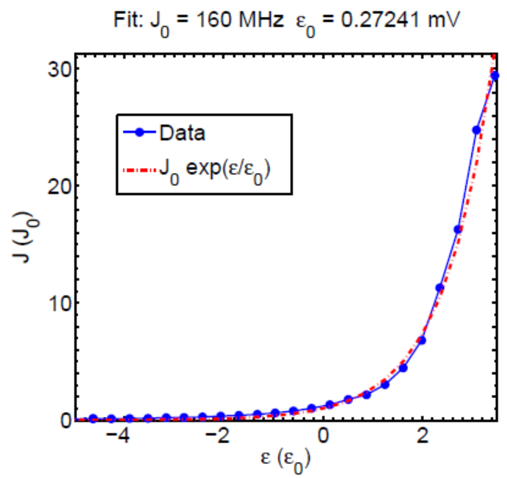
- 2D electron gas through hetero structure
- 2D confinement with topological electrodes
- Capture electrons in resulting double quantum dot

State:

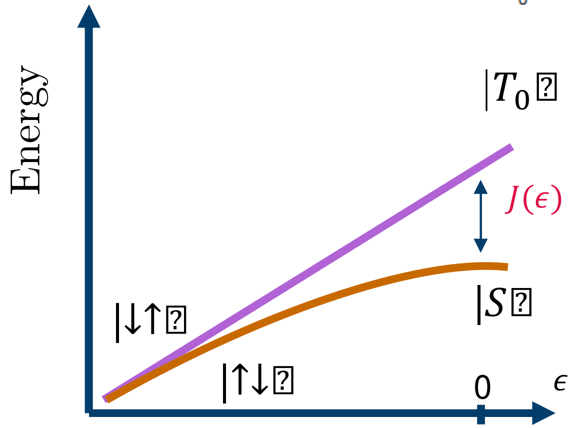
- Use spin of electrons to encode state of qubit

$$|0\rangle = |T_0\rangle, |1\rangle = |S\rangle$$

- State = energy state
- Manipulation through ϵ voltage signal



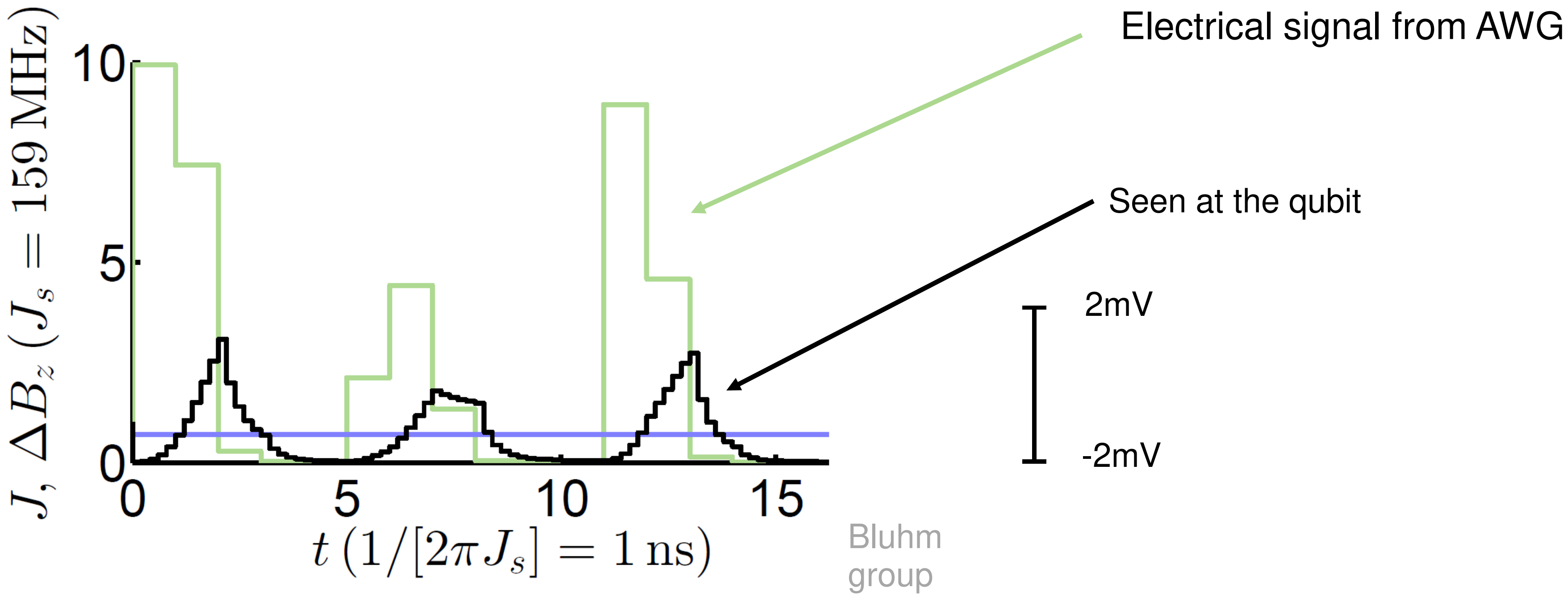
Bluhm group



BASIC QUANTUM COMPUTING

Operating a GaAs qubit

Use rectangular sequences:



Bluhm group

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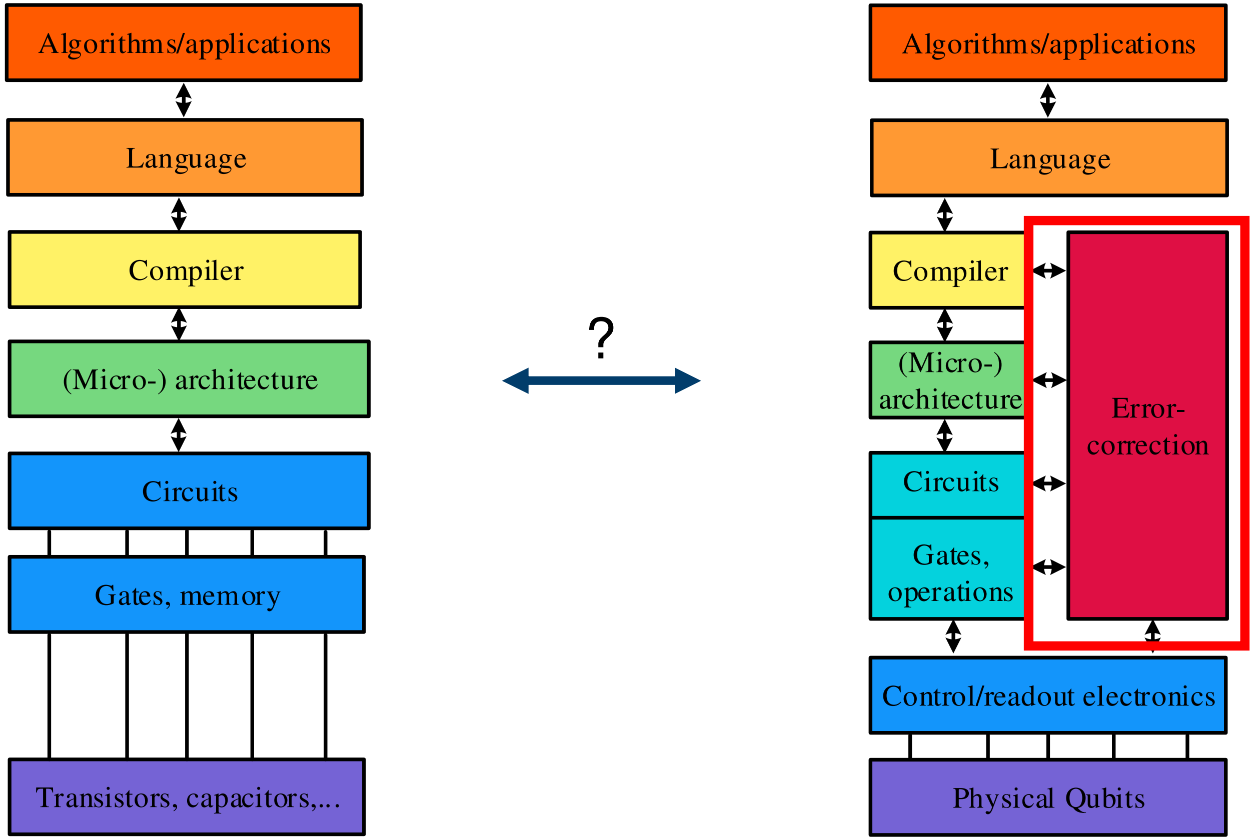


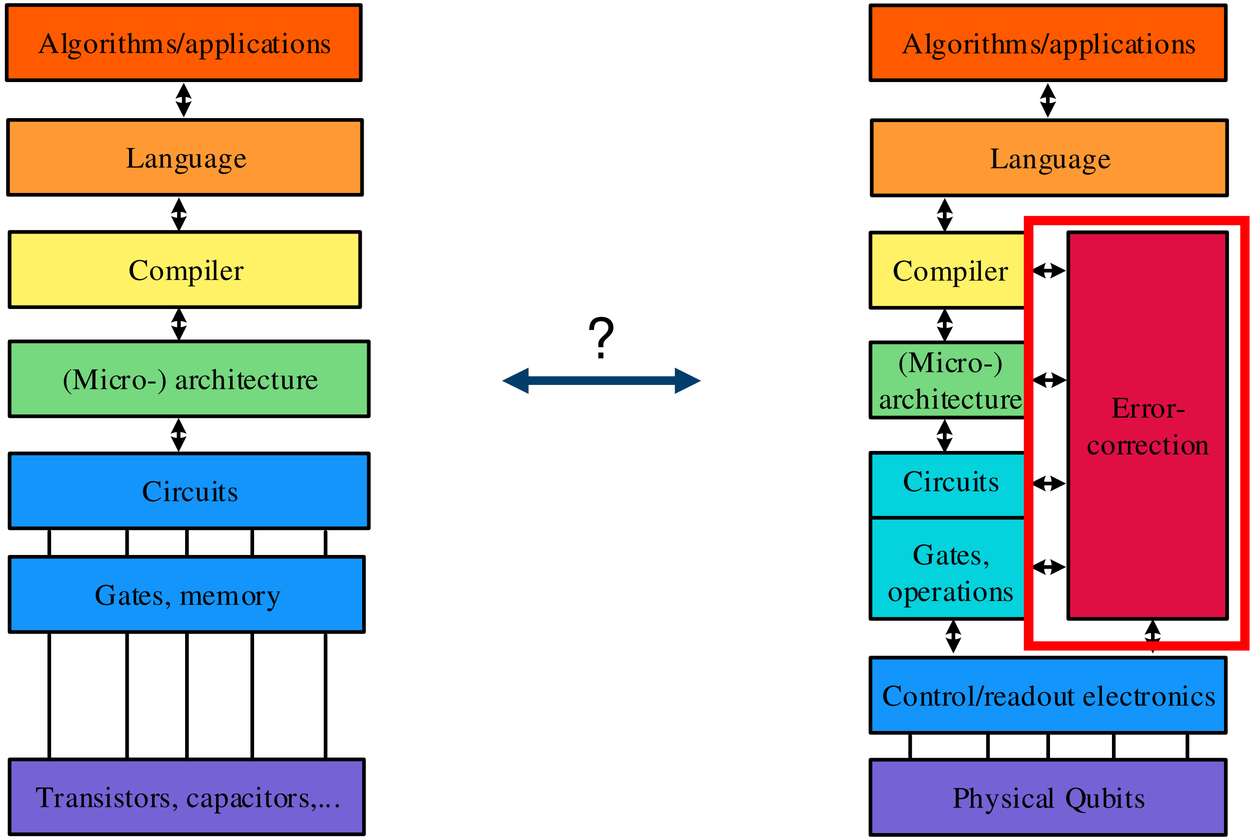
CLASSICAL VS QUANTUM COMPUTER

Error Correction

- Short storage (coherence) time
  - µs – s
- Unreliable operation
  - Gate error rate: MOSFET 10^{-16} vs Qubit $10^{-1} \sim 10^{-2}$

- Limitations for quantum error correction
  - No copying
  - Destructive detection
  - Continuous error

CLASSICAL VS QUANTUM COMPUTER



Number of qubits for 2048 bit Shor's algorithm (prime factorization)

>5 billion

1.3 billion

100.000

[1] Similarly taught in EE4575 and AP3421 at Delft University of Technology