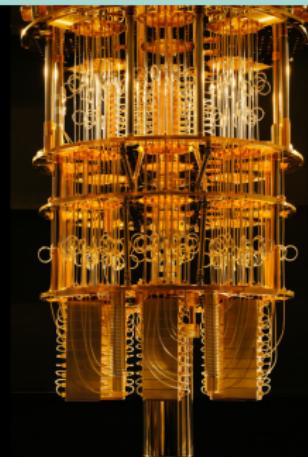
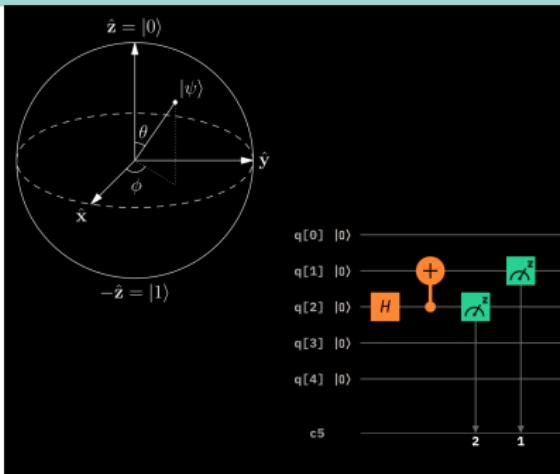


Physical Implementation of Quantum Computing

Martin Koppenhöfer

<https://www.quantumtheory-bruder.physik.unibas.ch/>



General outline

previous session

- introduction into quantum computing

this session

- which quantum-computing platforms exist?
- what are their benefits / drawbacks?
- how does one operate a quantum computer?
- **web-based** access on IBM's quantum computers

tomorrow's session

- programming IBM's quantum computers with **python**

Online resources

[https://www.quantumtheory-bruder.physik.unibas.ch/
people/martin-koppenhoefer/
quantum-computing-and-robotic-science-workshop.html](https://www.quantumtheory-bruder.physik.unibas.ch/people/martin-koppenhoefer/quantum-computing-and-robotic-science-workshop.html)

- installation guide for tomorrow's session
- material for tomorrow's session (will be uploaded later today)
- slides

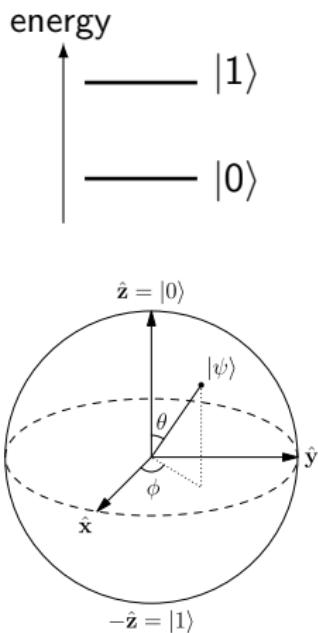
Outline of this session

- 1 Recap
- 2 What are properties of a good qubit?
- 3 Overview of quantum-computing platforms
- 4 Nuclear magnetic resonance (NMR)
- 5 Ions in electromagnetic traps
- 6 Electron spins in semiconductor quantum dots
- 7 Superconducting electrical circuits
- 8 Comparison of quantum-computing platforms
- 9 Operating a quantum processor
- 10 Cloud-based access

Recap

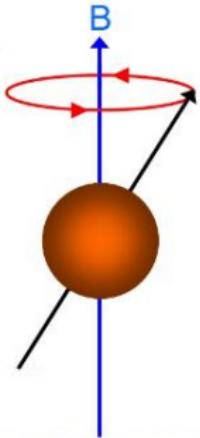
What are quantum bits (qubits)?

- a **classical computer** manipulates **bits**: possible states 0 or 1 are *discrete*
- a **quantum computer** manipulates **qubits** \equiv *quantum two-level systems*: possible states $(\alpha|0\rangle + \beta|1\rangle)$ are *continuous* α, β are complex numbers, $|\alpha|^2 + |\beta|^2 = 1$.
- measuring a **qubit** yields a **classical bit** (probabilistically)
- state of a qubit can be represented as a vector, e.g., in the z basis
 $|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

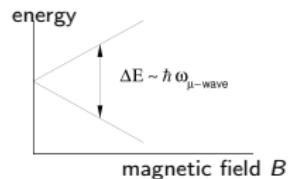


Recap

Example: electron in a magnetic field



- spin: quantum-mechanical property
- two states: $|\uparrow\rangle$ and $|\downarrow\rangle$
- states $|\uparrow\rangle$ and $|\downarrow\rangle$ have different energy in a magnetic field B
 - spin-up state $|\uparrow\rangle \rightarrow$ logical state $|0\rangle$
 - spin-down state $|\downarrow\rangle \rightarrow$ logical state $|1\rangle$
- applying magnetic fields at the level-splitting energy ΔE generates transitions $|\uparrow\rangle \leftrightarrow |\downarrow\rangle$

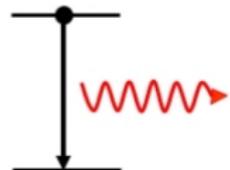


Recap

Decoherence

Transition of a quantum state to a classical state

$$|\psi\rangle = |\alpha| |0\rangle + e^{i\phi} \sqrt{1 - |\alpha|^2} |1\rangle$$



- **Relaxation:** Qubit makes the irreversible transition

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

on average: exponential decay with half-life period T_1

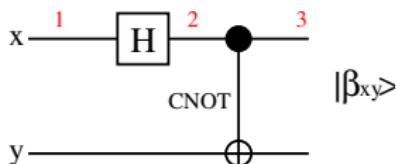
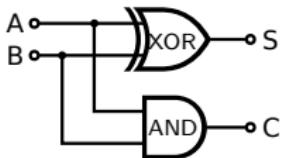
- **Dephasing:** Qubit loses the superposition

on average: half-life period T_2

Recap

What is a quantum algorithm?

- a **classical computer** manipulates a N -bit state by **logical gates**
- algorithms are built from a universal set of gates (e.g., the NAND gate)
- a **quantum computer** manipulates a N -qubit state by **quantum gates**
- algorithms are built from a universal set of quantum gates (e.g. H, T, and CNOT)



Recap

Single-qubit gates

- NOT gate: $\hat{X} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

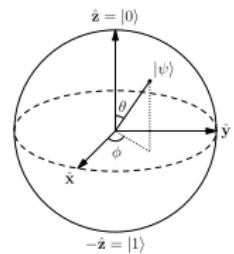
$$\hat{X} |0\rangle = |1\rangle$$

$$\hat{X} |1\rangle = |0\rangle$$

- Hadamard gate: $\hat{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$

$$\hat{H} |0\rangle = \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle)$$

$$\hat{H} |1\rangle = \frac{1}{\sqrt{2}} (|0\rangle - |1\rangle)$$



Recap

Controlled NOT gate (CNOT)

- 2-qubit gate
- flip second (target) qubit if first (control) qubit is $|1\rangle$:

$$|00\rangle \rightarrow |00\rangle$$

$$|01\rangle \rightarrow |01\rangle$$

$$|10\rangle \rightarrow |11\rangle$$

$$|11\rangle \rightarrow |10\rangle$$

$$\text{CNOT} = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}$$

- circuit diagram:

control qubit:

$$\alpha |0\rangle + \beta |1\rangle$$

target qubit:

$$|0\rangle$$

$$\alpha |00\rangle + \beta |11\rangle$$

How to build a quantum computer

- identify a two-level system as a part of a larger physical system
- find out how to initialize the qubit
- find out how to do gates and measurements

What are properties of a good qubit?

Di-Vincenzo criteria

Properties of a good qubit:

- ① **scalability**: build a large (e.g., 10^9) number of qubits
- ② **initialization**: prepare a well-defined initial quantum state
- ③ **long coherence time**: in comparison to the gate time
- ④ **universal set of quantum gates**: to construct all possible quantum gates
- ⑤ **measurement procedure**: to get the result of a calculation

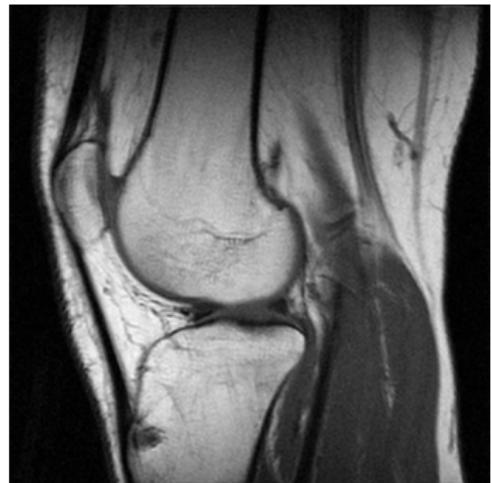
Overview of quantum-computing platforms

- spins in large molecules + NMR
- ions in electromagnetic traps
- neutral atoms in optical lattices
- optical quantum computing
- ^{31}P donor atoms in silicon
- electron spins in semiconductor quantum dots
- superconducting electrical circuits
 - flux qubit
 - charge qubit
 - phase qubit
 - transmon qubit
- topological qubits

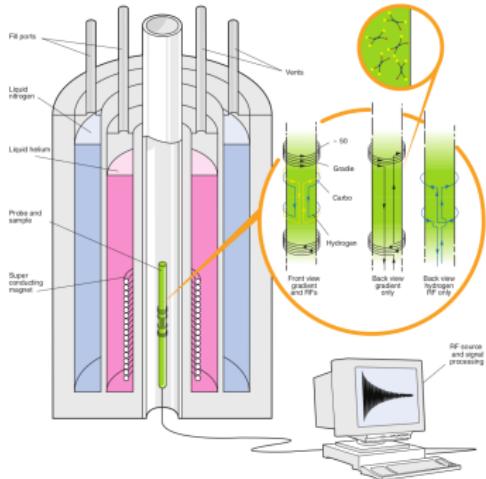


* online access

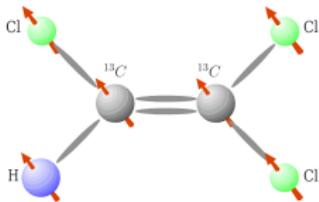
Nuclear magnetic resonance (NMR)



Nuclear magnetic resonance (NMR)



Trichloroethylene: 3 qubits



- use nuclei with spin $\frac{1}{2}$
- apply static magnetic field B to split the states $|\uparrow\rangle$ and $|\downarrow\rangle$
- single-qubit gates:
radio-frequency magnetic fields
- multi-qubit gates: use
interaction of spins within one
molecule
- readout: precessing spins induce
voltage in readout coils
- Shor's prime-factoring algorithm
demonstrated on 7 qubits

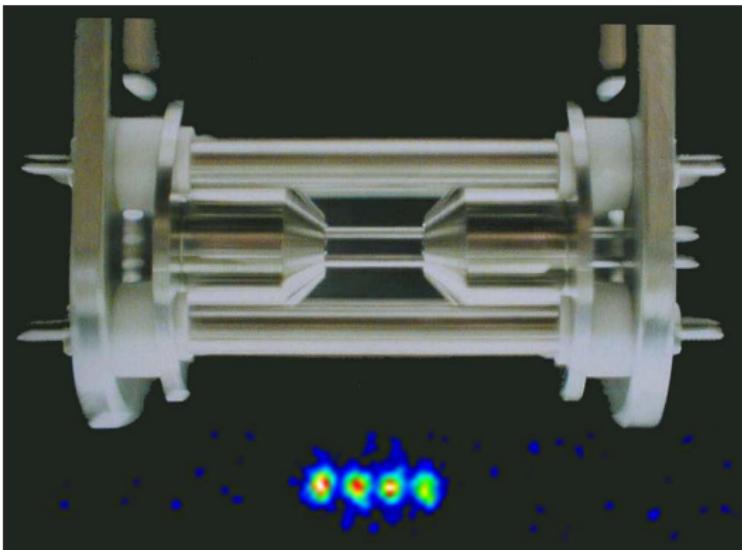
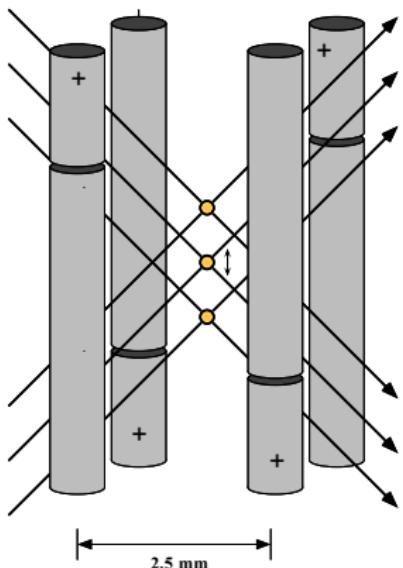
Nuclear magnetic resonance (NMR)

Di-Vincenzo benchmark

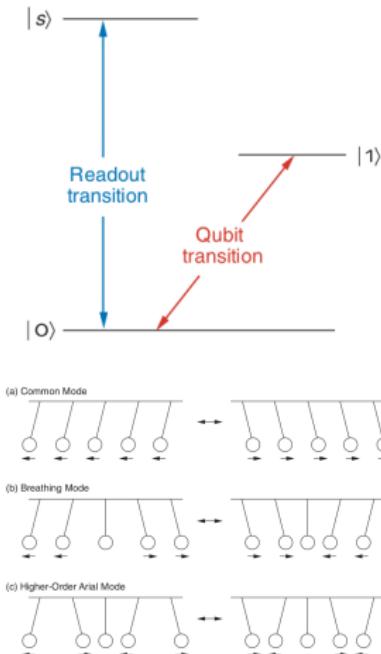
- scalability: ✗
- initialization: ✓
- long coherence time: ✓
- universal set of quantum gates: ✓
- measurement procedure: ✓

Ions in electromagnetic traps

- $\lesssim 50$ ions (e.g., ${}^9\text{Be}$, ${}^{40}\text{Ca}$) in harmonic electromagnetic trap



Ions in electromagnetic traps



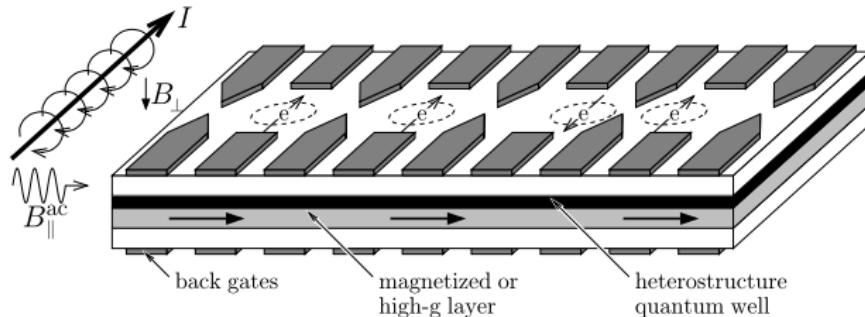
- qubit encoded in two long-lived internal states $|0\rangle$, $|1\rangle$ of an ion
- **single-qubit gates:** laser beams induce transitions $|0\rangle \leftrightarrow |1\rangle$
- **readout:** drive transition from $|0\rangle$ to short-lived state $|s\rangle$, detect photon emitted during relaxation $|s\rangle \rightarrow |0\rangle$.
- **multi-qubit gates:** ions repel each other
⇒ oscillation modes along the chain
⇒ useful for qubit-qubit interaction

Ions in electromagnetic traps

Di-Vincenzo benchmark

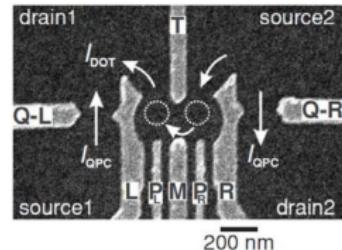
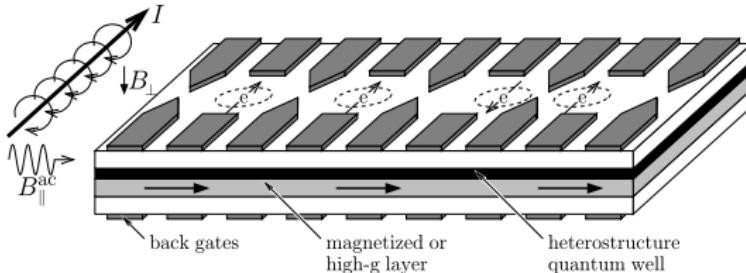
- scalability: ✗
- initialization: ✓
- long coherence time: ✓
- universal set of quantum gates: ✓
- measurement procedure: ✓

Electron spins in semiconductor quantum dots



- A two-dimensional electron gas (2DEG) can be realized in semiconductor heterostructures
- 2DEG can be structured by gate electrodes (negative potential repels electron gas under the electrode)
- **quantum dots** may be formed which contain a small number or only a single electron

Electron spins in semiconductor quantum dots



- B_{\perp} splits the states $|\uparrow\rangle$, $|\downarrow\rangle$
- single-qubit gates: apply time-dependent magnetic field $B_{\parallel}(t)$
- two-qubit gates using **exchange interaction** between spins of neighboring dots $\hat{H}_{\text{ex}} = \sum_{\langle i,j \rangle} J_{ij} \hat{S}_i \cdot \hat{S}_j$
coupling strength J_{ij} depends on **gate voltages**
- readout: single-electron transistor or quantum point contact

Electron spins in semiconductor quantum dots

Di-Vincenzo benchmark

- scalability: ✓ (semiconductor technology!)
- initialization: ✓
- long coherence time: ✓
- universal set of quantum gates: ✓
- measurement procedure: ✓

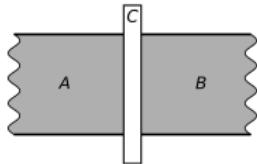
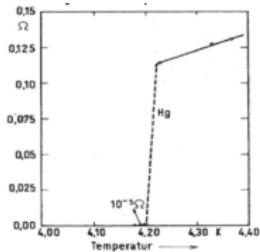
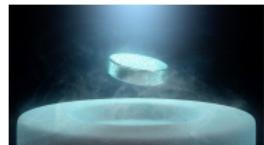
Superconducting electrical circuits

What is a superconductor?

- macroscopic quantum systems with zero resistance below a critical temperature T_c
- electrons form **Cooper pairs** characterized by a **macroscopic wavefunction** $\Psi = \sqrt{n_s} e^{i\varphi}$
- two superconductors (A, B) separated by an insulating oxide barrier (C) form a **Josephson junction**
- **Josephson effect:** even in the absence of a voltage across the Josephson junction, a supercurrent I can flow:

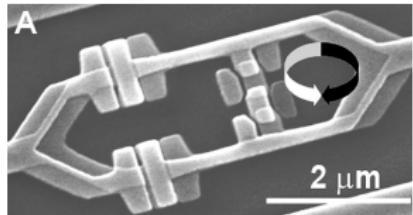
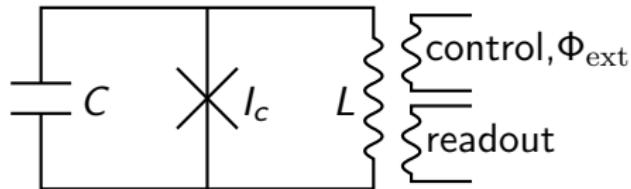
$$I = I_c \sin(\varphi_{\text{left}} - \varphi_{\text{right}})$$

$$\hat{H} = -E_J \cos(\varphi_{\text{left}} - \varphi_{\text{right}})$$



Superconducting electrical circuits

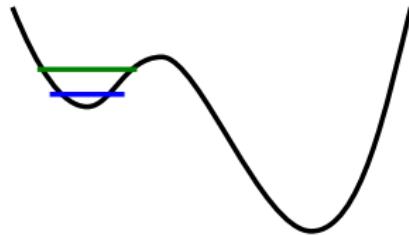
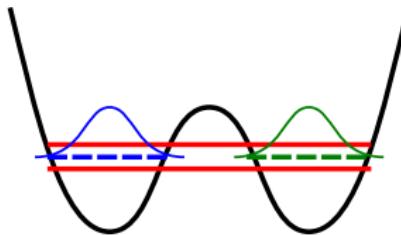
Flux and phase qubit



$$\hat{H} = \frac{\hat{Q}^2}{2C} - E_J \cos(\hat{\varphi}) - \frac{(\hat{\varphi} - \Phi_{\text{ext}})^2}{2L}$$

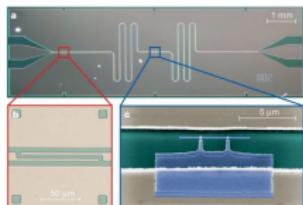
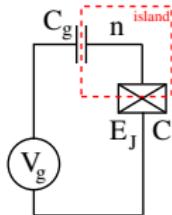
Flux qubit: $\Phi_{\text{ext}} = \frac{\Phi_0}{2}$
superpositions of $|0\rangle$ and $|1\rangle$

Phase qubit: $\Phi_{\text{ext}} \approx \Phi_0 = \frac{\hbar}{2e}$
states $|0\rangle$ and $|1\rangle$ in same well



Superconducting electrical circuits

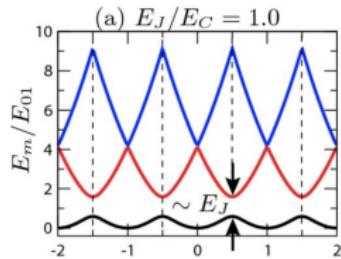
Charge and transmon qubit



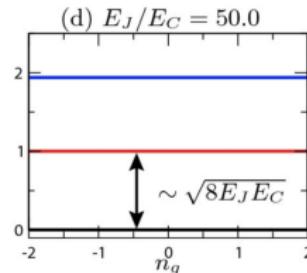
control & readout

$$\hat{H} = E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\varphi})$$

Charge qubit: $E_C \gg E_J$
superpositions of 0 or 1 Cooper pairs on the island

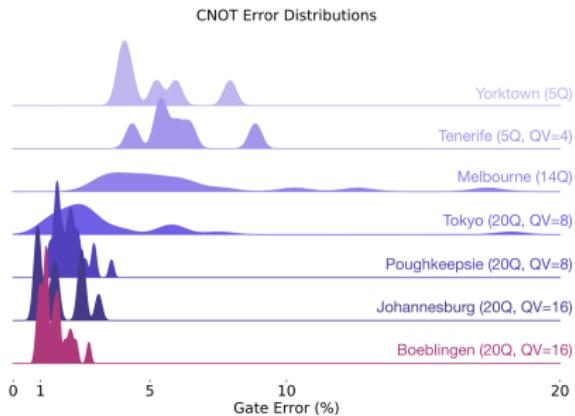
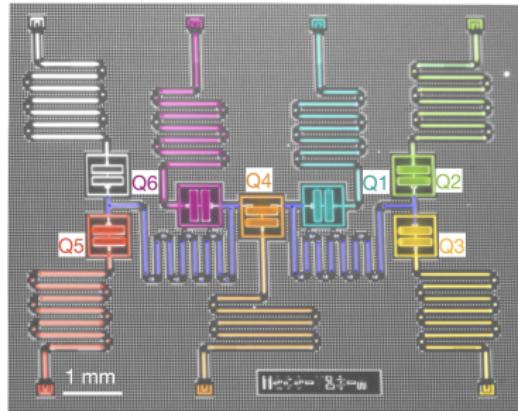


Transmon: $E_C \ll E_J$
Lowest eigenstates in an anharmonic potential



Superconducting electrical circuits

Charge and transmon qubit



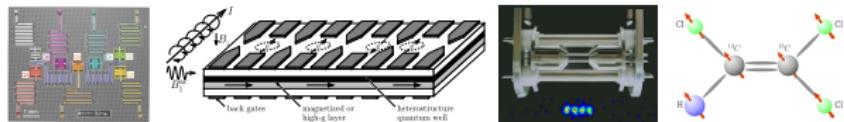
- seven fixed-frequency transmon qubits
- each qubit is coupled to a microwave resonator to do single-qubit gates and readout
- several qubits are coupled by microwave resonators to implement multi-qubit gates

Superconducting electrical circuits

Di-Vincenzo benchmark

- scalability: ✓
- initialization: ✓
- long coherence time: ✓
- universal set of quantum gates: ✓
- measurement procedure: ✓

Comparison of quantum-computing platforms



	superconducting qubit	electron spin qubit	trapped ions	NMR
footprint	$\approx \mu\text{m}$	$0.1 \mu\text{m}$	spacing $10 \mu\text{m}$	mm
scalability	yes	yes	complicated	no
energy gap	$1 - 20 \text{ GHz}$	$1 - 10 \text{ GHz}$	$10^5 - 10^6 \text{ GHz}$	MHz
temperature	10 mK	100 mK	μK	300 K
single-qubit gate time τ_1	$\approx \text{ns}$	10 ns	μs	ms
two-qubit gate time τ_2	$10 - 50 \text{ ns}$	$0.2 \mu\text{s}$	$100 \mu\text{s}$	10 ms
coherence time T_2	$10 - 100 \mu\text{s}$	ms – s	0.1 s	10 s
1-qubit gate fidelity (%)	98 – 99.9	98 – 99.9	99.1 – 99.9999	98 – 99
2-qubit gate fidelity (%)	96 – 99.4	89 – 96	97 – 99.9	98
initialization	yes	yes	yes	ensemble
readout fidelity (%)	99	97	99.99	ensemble

[Xiang et al., Rev. Mod. Phys. 85, 623 (2013)]

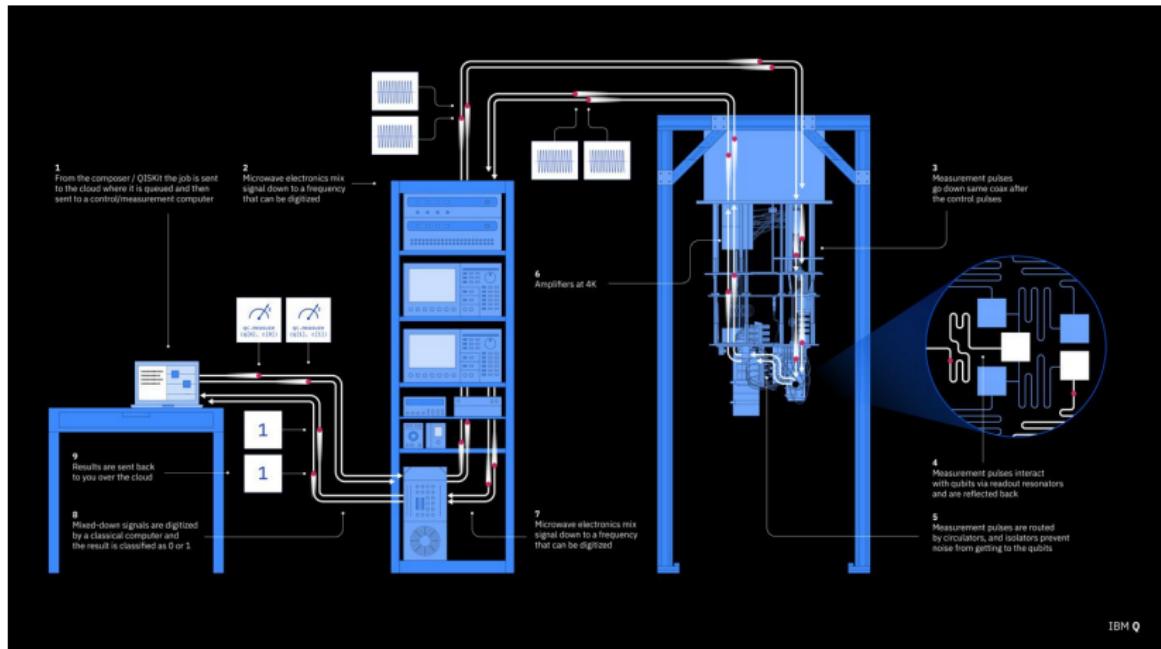
[Resch et al., arXiv:1905.07240 (2019)]

[Keith et al., Phys. Rev. X 9, 041003 (2019)]

$5 \text{ GHz} \approx 250 \text{ mK}$

Operating a quantum processor

The lab around a quantum processor



Cloud-based access

The dashboard

The screenshot shows the IBM Quantum Experience dashboard. On the left, there's a sidebar with icons for navigation and a search bar. The main area has a "Welcome" section for Martin Koppenhoefer, followed by a "Recent circuits" list, a "Your backends" list, and sections for "Pending results" and "Latest results".

Welcome
Martin
Koppenhoefer

Your providers
IBM Q Research
IBM Q Network member
[See more](#)

Recent circuits (3)

Name	Last updated
Untitled circuit	37 minutes ago
Bell_state_00_generation	6 days ago
superdense_coding	14 days ago

[View All](#)

Pending results (0)
You have no circuit runs in the queue.

Latest results

Status	Run date	Name or Id	Tags	Provider	Service
COMPLETED	2023-08-22T10:00:00Z	ibmq_bogota			

Your backends (12)

ibmq_casablanca (7 qubits, QV32) Queue: 2 jobs Reservable
ibmq_bogota (5 qubits, QV32) Queue: 6 jobs Reservable
ibmq_santiago (5 qubits, QV32) Queue: 16 jobs Reservable

https://quantum-computing.ibm.com/

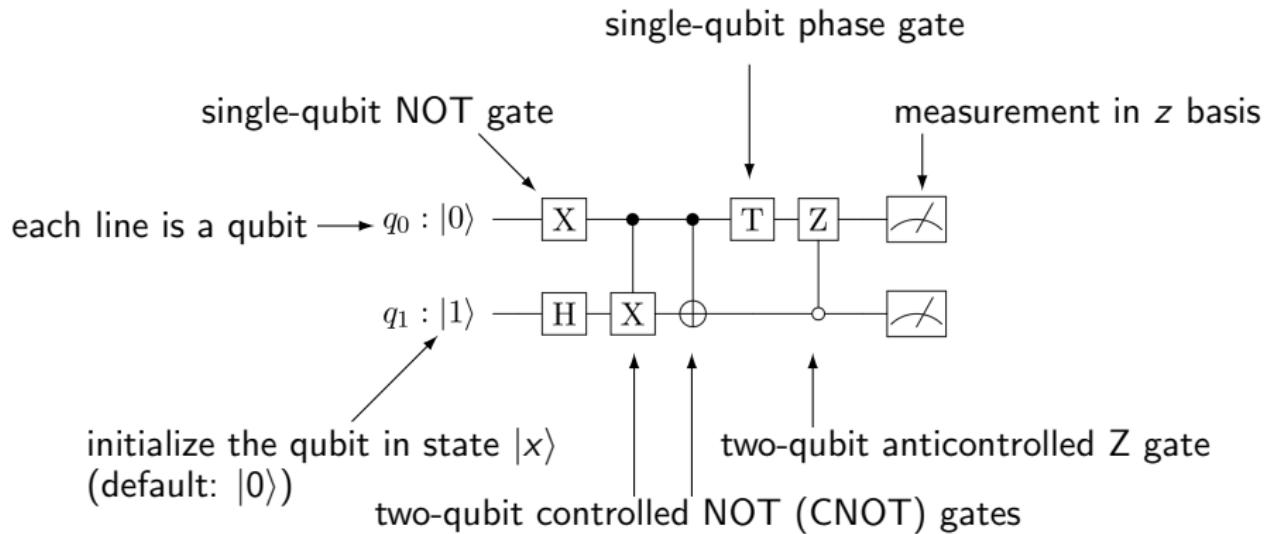
Cloud-based access

A quantum processor



Cloud-based access

Quantum circuits



$$\hat{X} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \hat{Z} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \hat{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$

Cloud-based access

The circuit editor

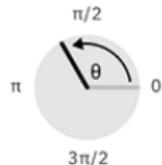
The screenshot shows the IBM Quantum Experience web interface. At the top, there's a navigation bar with 'IBM Quantum Experience' and links for 'File', 'Edit', 'Inspect', 'View', 'Share', and 'Help'. To the right of the navigation is a search bar and a user icon. Below the navigation, a blue bar displays 'Run on ibmq_santiago'. The main area is titled 'Circuits / Untitled circuit'. On the left, a toolbar contains icons for various quantum operations: H, \oplus , \ominus , $\oplus\ominus$, $\ominus\oplus$, T, S, Z, T^\dagger , S^\dagger , P, RZ, $|0\rangle$, not , if, \dots , \sqrt{X} , and a plus sign. Below this toolbar is a row of single-qubit rotation gates: \sqrt{X}^\dagger , Y, RX, RY, U, RX, and RZZ. A '+ Add' button is also present. The circuit itself has four qubits labeled q₀, q₁, q₂, and q₃. The first two qubits have open circles at their ends, while q₂ has a '+' sign and q₃ has a question mark. To the right of the circuit, there's a section titled 'Jobs from this circuit' with a 'View all' link. The bottom of the interface features a large, bold text overlay: 'Glossary of gates and operations in Docs'.

Cloud-based access

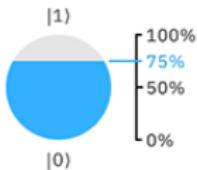
Visualizing the state of a single qubit

$$\sqrt{1 - |\alpha|} |0\rangle + e^{i\theta} |\alpha| |1\rangle$$

- relative phase θ of a superposition



- probability $|\alpha|^2$ to measure the $|1\rangle$ state



- entanglement

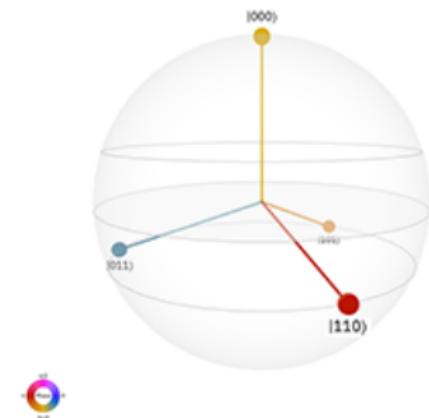


Cloud-based access

Visualizing the state of a quantum register

$$\begin{aligned} & \alpha_{000} |000\rangle \\ & + \alpha_{100} |100\rangle + \alpha_{010} |010\rangle + \alpha_{001} |001\rangle \\ & + \alpha_{110} |110\rangle + \alpha_{101} |101\rangle + \alpha_{011} |011\rangle \\ & + \alpha_{111} |111\rangle \end{aligned}$$

- layer n contains all states with n qubits in state $|1\rangle$
- thickness of node of state $|x\rangle$: $|\alpha_x|$
- color of node of state $|x\rangle$: $\arg(\alpha_x)$



Generating Bell states

Quantum circuit

$$|\beta_{00}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

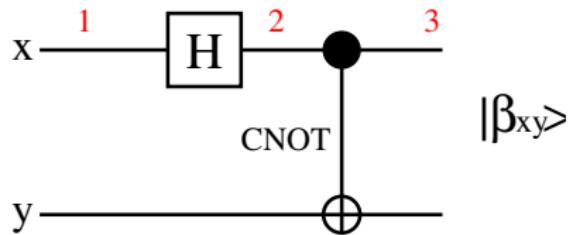
$$|\beta_{01}\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|\beta_{10}\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|\beta_{11}\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

General expression:

$$|\beta_{xy}\rangle = \frac{1}{\sqrt{2}}(|0y\rangle + (-1)^x |1\bar{y}\rangle)$$



1 input state: $|xy\rangle = |00\rangle$

2 apply Hadamard gate

$$\hat{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}:$$

$$\frac{1}{\sqrt{2}}(|00\rangle + |10\rangle)$$

3 apply CNOT gate:

$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) = |\beta_{00}\rangle$$

Generating Bell states

Reminder: Entanglement

- Bell states are a crucial resource for quantum algorithms because they are entangled
- classical N -bit states can be “factorized”

Example: classical state (11)

- bit 1 is in state “1”, bit 2 is in state “1”
- equivalent quantum state: $|11\rangle = |1\rangle \otimes |1\rangle$
- But there are quantum states that cannot be factorized

Example: state $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \neq |\psi_1\rangle \otimes |\psi_2\rangle$

- system can only be described as a whole

Generating Bell states

Reminder: Entanglement

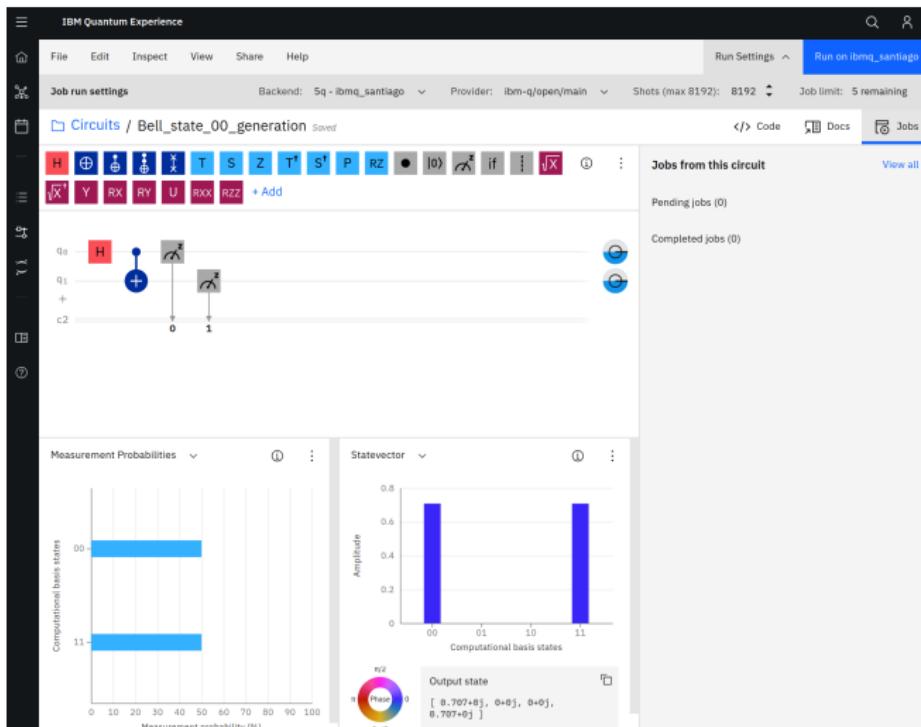
- entanglement \Rightarrow correlations

$$\frac{1}{\sqrt{2}} (|00\rangle + |11\rangle)$$

- What happens if we measure qubit 1 and 2 in the z basis?
- either we get 0 for qubit 1 and 0 for qubit 2 (probability $\frac{1}{2}$)
- or we get 1 for qubit 1 and 1 for qubit 2 (probability $\frac{1}{2}$)
- but never any “mixed” result

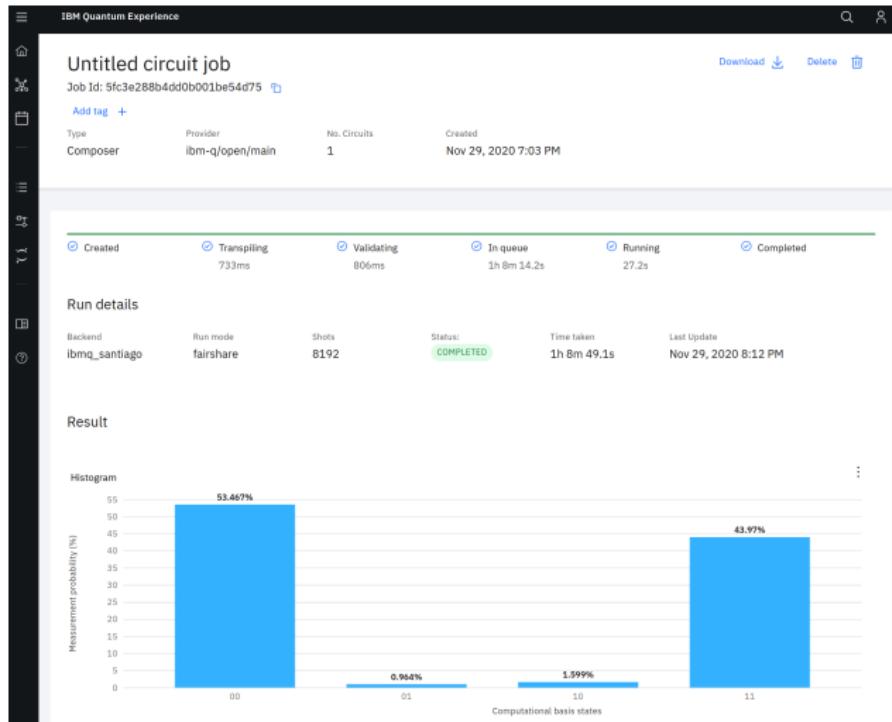
Generating Bell states

Online demonstration



Generating Bell states

Online demonstration



Educational material

Start your path towards
learning *Quantum Algorithms*

Learning resources

The below are designed and created by the Qiskit team.
However, we recommend a familiarity with [linear algebra](#)
and [Python](#) from these trusted resources.

<https://qiskit.org/learn>

Qiskit textbook

Youtube series *Coding with Qiskit*

Online course *Introduction to QC*

All resources

Beginner

Advanced

Time to spend learning

- any
- 1 minute
- 1 day
- 1 week
- 1 month
- 1 year



Qiskit Textbook

The Qiskit Textbook is a free digital open source textbook that will teach you the concepts of quantum computing while you learn to use Qiskit.

Read the textbook

Material for next session

The screenshot shows a Jupyter Notebook interface with the title "jupyter store_account_information_locally (autosaved)". The notebook has a toolbar with File, Edit, View, Insert, Cell, Kernel, Widgets, Help, and a Trusted status indicator. The URL is py3.7_qiskit0.23.1. The notebook contains two sections:

Test your qiskit installation

Import the qiskit package:

```
In [ ]: import qiskit
```

Display its version information. This command should output:

```
{'qiskit-terra': '0.16.1', 'qiskit-aer': '0.7.1', 'qiskit-ignis': '0.5.1', 'qiskit-lbmq-provider': '0.11.1', 'qiskit-aqua': '0.8.1', 'qiskit': '0.23.1'}
```

```
In [ ]: print(qiskit.__qiskit_version__)
```

Store your IBM token locally

In []: from qiskit import IBMQ

Copy your IBM token on <https://quantum-computing.ibm.com/account> and put in the following command:

```
In [ ]: IBMQ.save_account('PUT YOUR IBM TOKEN HERE')
```

The last command saved the IBM token to your local hard disk. We can now load the account from this file:

```
In [ ]: IBMQ.load_account()
```

As a check, the following command should output your token and the url <https://auth.quantum-computing.ibm.com/api>:

```
In [ ]: IBMQ.active_account()
```

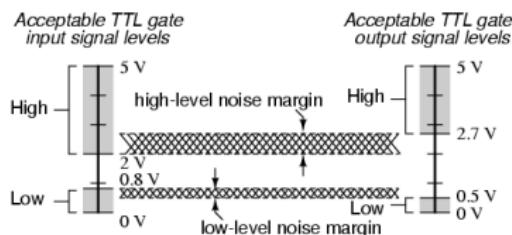
Your IBM token is your personal key to the IBM quantum computing experience. Don't share it with anyone.

Download link

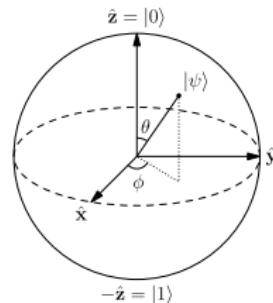
Thank you
for your attention.

Backup slides

Discrete vs. continuous states



[<https://www.allaboutcircuits.com/>]



$$\text{consider } \hat{H}_\varepsilon = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 + i\varepsilon \\ 1 & -1 - i\varepsilon \end{pmatrix}:$$

$$\hat{H}\hat{H}|0\rangle = |0\rangle$$

$$\hat{H}_\varepsilon\hat{H}_\varepsilon|0\rangle = \left(1 + i\frac{\varepsilon}{2}\right)|0\rangle - i\frac{\varepsilon}{2}|1\rangle$$