



Pritzker School of Molecular Engineering

Physical Implementation of Quantum Computing

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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

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

Outline of this session

🕕 Recap

- What are properties of a good qubit?
- Overview of quantum-computing platforms
- 4 Nuclear magnetic resonance (NMR)
- Ions in electromagnetic traps
- Electron spins in semiconductor quantum dots
- Superconducting electrical circuits
- Comparison of quantum-computing platforms
- Operating a quantum processor
- 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
 = quantum two-level systems:

possible states $(\alpha|0\rangle + \beta|1\rangle)$ are *continuous*

 $\alpha,\,\beta$ are complex numbers, $|\alpha|^2+|\beta|^2=1.$

- measuring a <u>qubit</u> 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: $|\uparrow
 angle$ and $|\downarrow
 angle$
- states $\left|\uparrow\right\rangle$ and $\left|\downarrow\right\rangle$ have different energy in a magnetic field B
 - spin-up state $\left|\uparrow\right\rangle\rightarrow$ logical state $\left|0\right\rangle$
 - ${\scriptstyle \bullet }$ spin-down state $\left| \downarrow \right\rangle \rightarrow$ logical state $\left| 1 \right\rangle$
- 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

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

• Relaxation: Qubit makes the irreversible transition

|1
angle
ightarrow |0
angle

on average: exponential decay with half-life period $\ensuremath{\mathcal{T}}_1$

• Dephasing: Qubit loses the superposition on average: half-life period T₂



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 $|1\rangle$:



o circuit diagram:

control qubit:
$$\alpha |0\rangle + \beta |1\rangle$$

target qubit: $|0\rangle$ \longrightarrow $\alpha |00\rangle + \beta |11\rangle$

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:

- scalability: build a large (e.g., 10^9) number of qubits
- initialization: prepare a well-defined initial quantum state
- Iong coherence time: in comparison to the gate time
- universal set of quantum gates: to construct all possible quantum gates
- 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
- ³¹P 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: X
- initialization:
- Iong coherence time:
- universal set of quantum gates:
- measurement procedure:

Ions in electromagnetic traps

 $\, \bullet \, \lesssim 50$ 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
 - \Rightarrow oscillation modes along the chain
 - \Rightarrow useful for qubit-qubit interaction

Ions in electromagnetic traps

Di-Vincenzo benchmark

- scalability: X
- initialization:
- Iong 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 $|\uparrow
 angle$, $|\downarrow
 angle$
- single-qubit gates: apply time-dependent magnetic field $B_{\parallel}(t)$
- two-qubit gates using exchange interaction between spins of neighboring dots $\hat{H}_{ex} = \sum_{\langle i,j \rangle} J_{ij} \hat{S}_i \cdot \hat{S}_j$ 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:
- Iong coherence time:
- universal set of quantum gates:
- measurement procedure:

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:

$$I = I_{\rm c} \sin(\varphi_{\rm left} - \varphi_{\rm right})$$

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

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: $\Phi_{ext} = \frac{\Phi_0}{2}$ superpositions of $| \circlearrowleft \rangle$ and $| \circlearrowright \rangle$



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



Charge and transmon qubit



control & readout

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

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



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

Di-Vincenzo benchmark

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

Comparison of quantum-computing platforms



	superconducting qubit	electron spin qubit	trapped ions	NMR
footprint	$\approx \mu m$	0.1 μm	spacing 10 μm	mm
scalability	yes	yes	complicated	no
energy gap	$1-20\mathrm{GHz}$	$1-10\mathrm{GHz}$	$10^5 - 10^6 { m GHz}$	MHz
temperature	10 mK	$100 \mathrm{mK}$	μΚ	300 K
single-qubit gate time τ_1	$\approx ns$	10 ns	μs	ms
two-qubit gate time τ_2	$10-50 \mathrm{ns}$	0.2 μs	100 μs	$10\mathrm{ms}$
coherence time T_2	$10-100\mu s$	ms - s	0.1 s	$10 \mathrm{s}$
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)]

 $5\,{\rm GHz}\approx 250\,{\rm mK}$

Operating a quantum processor

The lab around a quantum processor



The dashboard

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A quantum processor

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Cloud-based access Quantum circuits single-qubit phase gate single-qubit NOT gate measurement in z basis each line is a qubit $\longrightarrow q_0 : |0\rangle \longrightarrow |\overline{X}|$ Η initialize the qubit in state $|x\rangle$ two-qubit anticontrolled Z gate (default: $|0\rangle$) two-qubit controlled NOT (CNOT) gates $\begin{pmatrix} 0 & 1 \end{pmatrix}$ $\hat{\tau}$ $\begin{pmatrix} 1 & 0 \end{pmatrix}$ $\hat{\mu}$ $\begin{pmatrix} 1 & (1 & 1) \end{pmatrix}$ τ $\begin{pmatrix} 1 & 0 \end{pmatrix}$ Ŷ

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

The circuit editor

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Visualizing the state of a single qubit

$$\sqrt{1-\left|lpha
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angle+e^{i heta}\left|lpha
ight|\left|1
ight
angle$$



entanglement



 $\pi/2$

θ,

 $3\pi/2$

100% 75% 50%

Visualizing the state of a quantum register

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

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



Quantum circuit

$$\begin{split} |\beta_{00}\rangle &= \frac{1}{\sqrt{2}} (|00\rangle + |11\rangle) \\ |\beta_{01}\rangle &= \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle) \\ |\beta_{10}\rangle &= \frac{1}{\sqrt{2}} (|00\rangle - |11\rangle) \\ |\beta_{11}\rangle &= \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle) \end{split}$$

General expression:

$$|eta_{xy}
angle = rac{1}{\sqrt{2}}(|0y
angle + (-1)^x |1ar{y}
angle)$$



- 1 input state: |xy
 angle = |00
 angle
- 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:

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

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"
- ${\scriptstyle \bullet }$ equivalent quantum state: $|11\rangle =|1\rangle \otimes |1\rangle$

• But there are quantum states that cannot be factorized

Example: state $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \neq |\psi_1\rangle \otimes |\psi\rangle_2$

• system can only be described as a whole

Reminder: Entanglement

• entanglement \Rightarrow correlations

$$rac{1}{\sqrt{2}}\left(\ket{00} + \ket{11}
ight)$$

- 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

Online demonstration



Online demonstration

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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*



Material for next session

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			The last command saved the IBM token to your local hard disk. We can now load the account from this file:			
	In	L1:	IBMQ.load_account()			
			As a check, the following command should output your token and the url https://auth.guantum-computing.ibm.com/api:			
	In	L1:	IBMQ.active_account()			
			Your IBM token is your personal key to the IBM quantum computing experience. Don't share it with anyone.			
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Thank you for your attention.

Backup slides

Discrete vs. continuous states





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

$$\hat{H}\hat{H}\ket{0} = \ket{0}$$

 $\hat{H}_{arepsilon}\hat{H}_{arepsilon}\ket{0} = \left(1 + irac{arepsilon}{2}\ket{0} - irac{arepsilon}{2}\ket{1}$