Superconducting circuits I

Demonstration of conditional gate operation using superconducting charge qubits

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nature

LETTERS

Demonstration of controlled-NOT quantum gates on a pair of superconducting quantum bits

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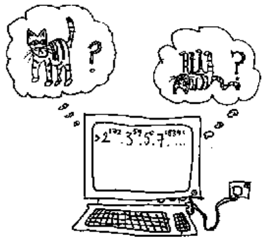
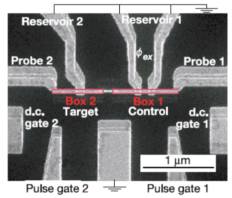
Outline

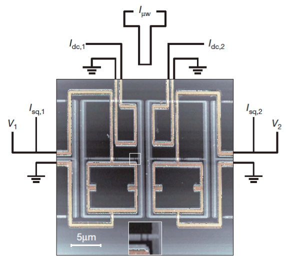
- Motivation



- C-NOT gate
- First realization of C-NOT gate with CPBs



- C-Not gate with flux qubits



- Comparison and Summary

Motivation

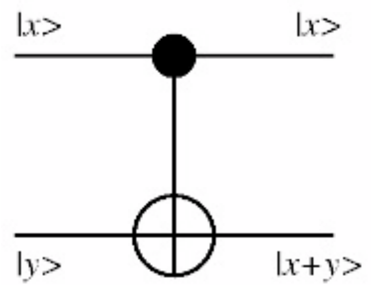
- Approaching the goal of quantum computation
- Fullfilling DiVincenzo criteria
- Superconducting quantum bits as building blocks for a quantum computer
- High fidelity gate operation

c-NOT gate

- Single qubit operation & c-NOT gate form a universal set of gates *(→ any computation can be done using these gates)*

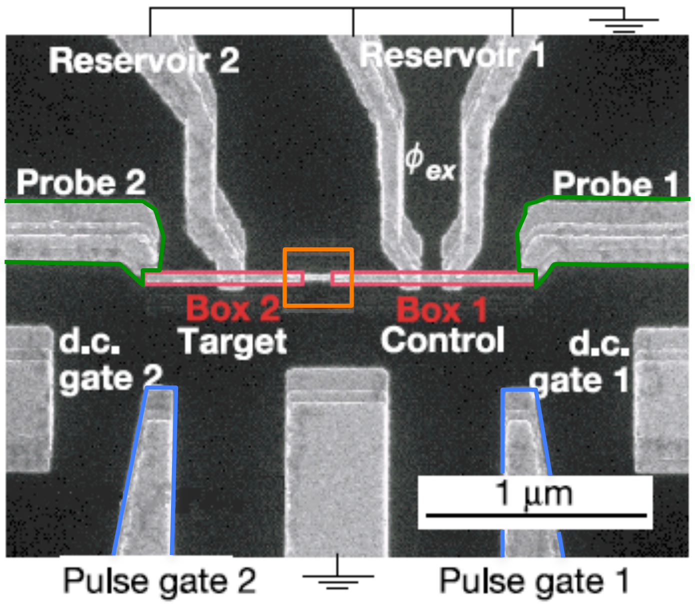
- Definition:

  „The target qubit is flipped if and only if the control qubit is in a given state“



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

The sample



Requirements:

- 2 two-level systems
- capacitive coupling between qubits

→ four-level system

- gates for independent control
- probes for read-out
- control bit tuned with B-field

Hamiltonian describing the system:

$$H = \sum_{n_1,n_2=0,1} E_{n_1 n_2} \mid n_1, n_2\rangle\langle n_1, n_2 \mid - \frac{E_{J1}}{2} \sum_{n_2=0,1} (\mid 0\rangle\langle 1 \mid + \mid 1\rangle\langle 0 \mid)\otimes \mid n_2\rangle\langle n_2 \mid - \frac{E_{J2}}{2} \sum_{n_1=0,1} \mid n_1\rangle\langle n_1 \mid \otimes(\mid 0\rangle\langle 1 \mid + \mid 1\rangle\langle 0 \mid)$$

electrostatics

Josephson coupling of box 1

Josephson coupling of box 2

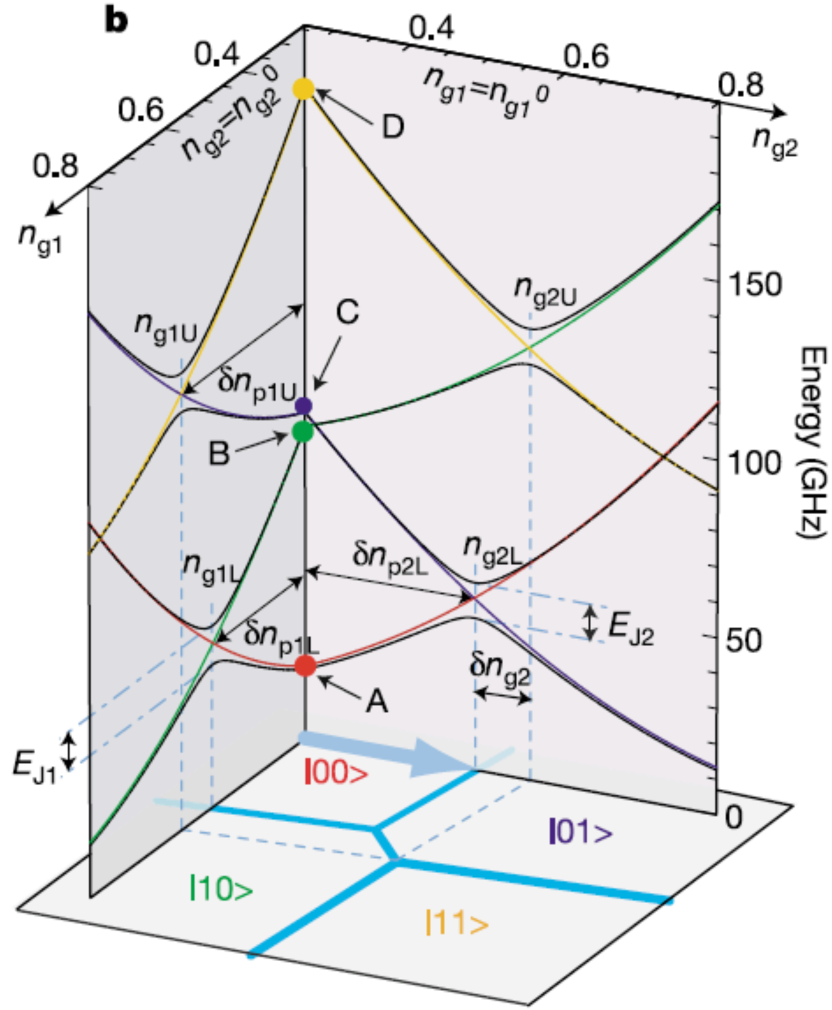
Energy band diagram

Eigenenergies of system at constant values for n_{g1} and n_{g2}

(number of excess Cooper pairs on respective box)

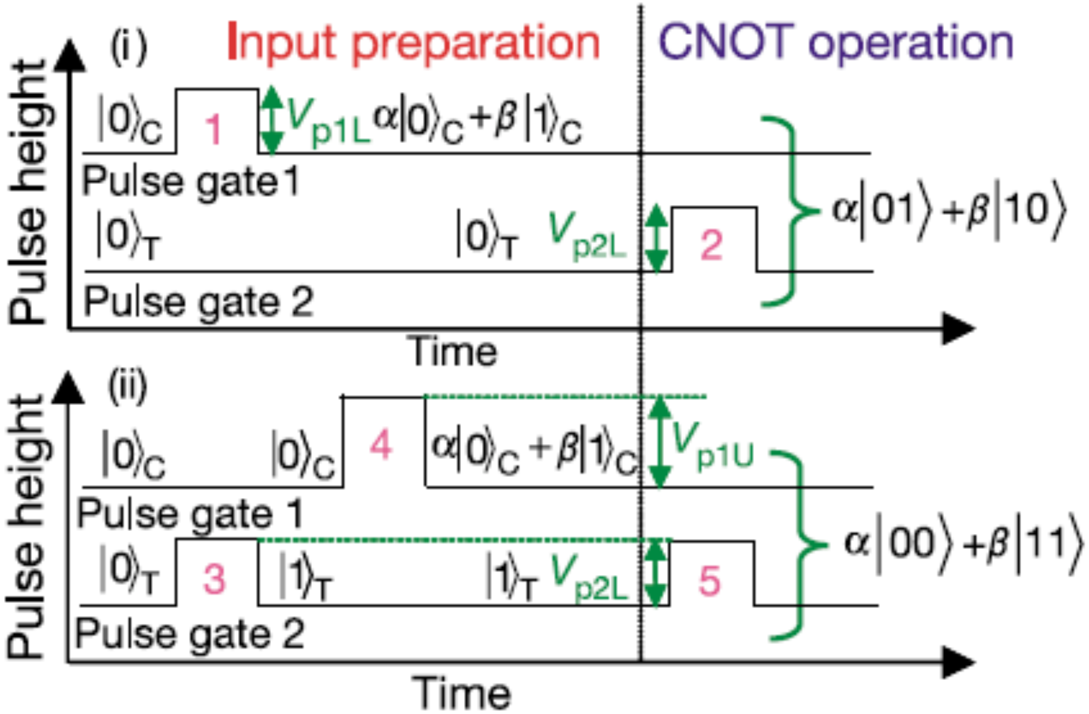
Determining possible outcomes of different pulse schemes

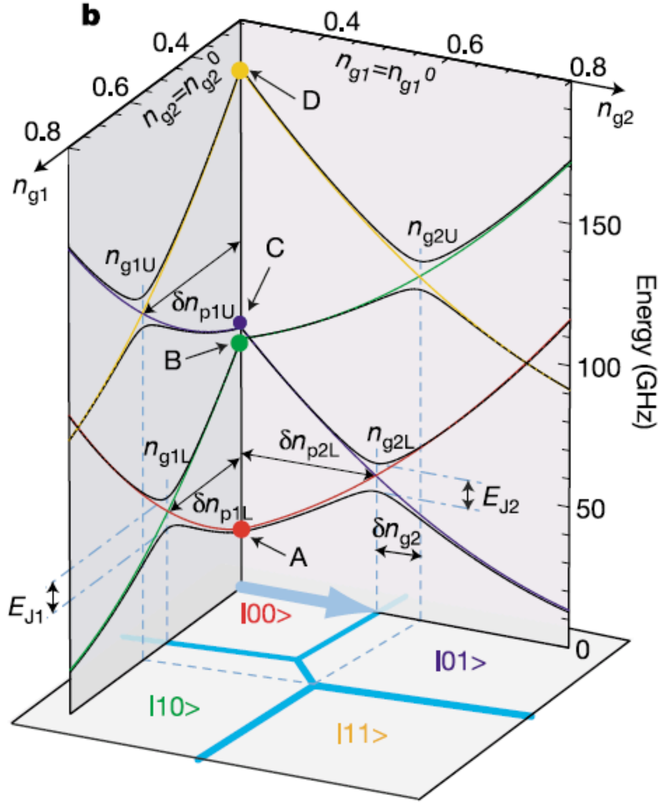
→ Controlled gate operation can be implemented



Pulse scheme and C-NOT operation

1. Preparation of specific input state
2. Applying c-NOT operation





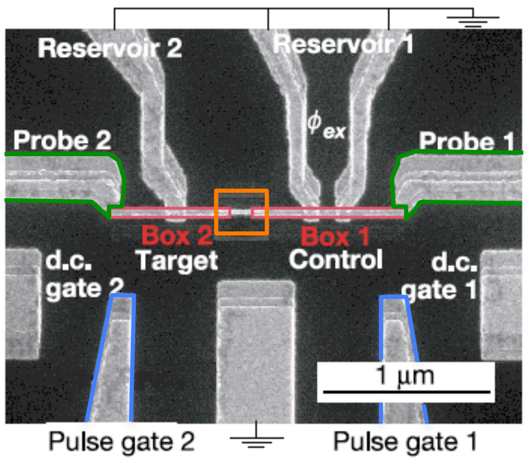
→ *Creation of entangled states*

Tunability and read-out

Periodic modulation of E_{J1} due to SQUID-geometry: $E_{J1} = E_{J1max}|\cos\left(\pi \frac{\phi_{ex}}{\phi_0}\right)|$

Recording JQP current through probe 1 and 2 (I is proportional to n_g)

→ read-out of state

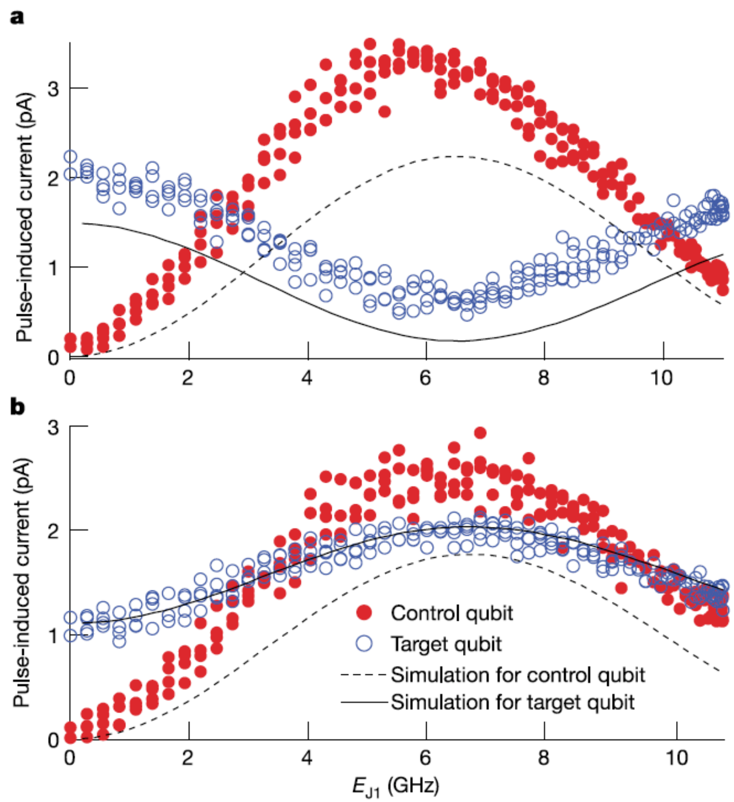


$\alpha\,|\,01\rangle + \beta\,|\,10\rangle$

pulse scheme (i)

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

pulse scheme (ii)

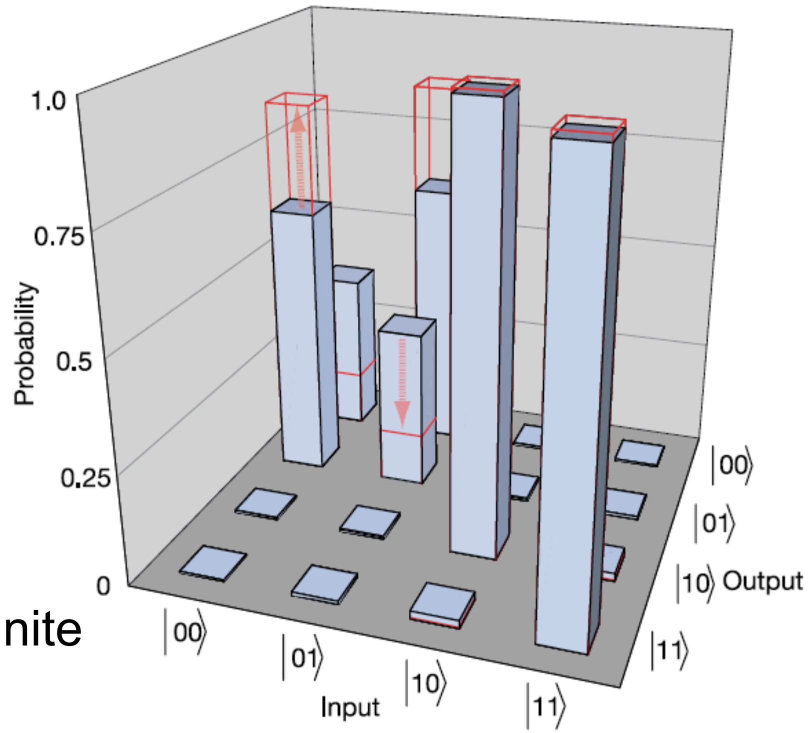


Simulation: Time evolution of density matrix

Truth table

Read-out method does not allow for individual measurement of the four states

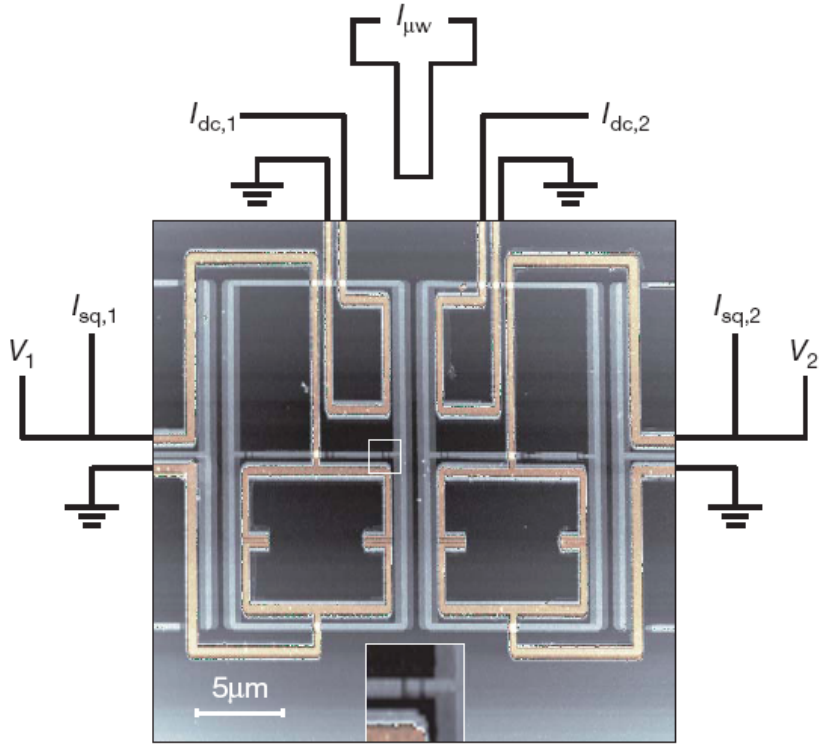
→ Calculation of time evolution of four perfect input states under gate operation pulse



Deviation from expected accuracy due to finite rise/fall time of pulse

→ Improving pulse shape and the coupling E_m

Coupled qubits set-up



Requirements:

- single pair of coupled flux qubits
- Inductive coupling between qubits
- Either qubit can be control or target qubit due to symmetry
- ➢ 4 level system

Set-up:

- two '8' shape flux qubits consisting of a superconducting loop interrupted by 3 Josephson junctions
- Two SQUIDs used as switching quantum state detectors

Hamiltonian describing the system:

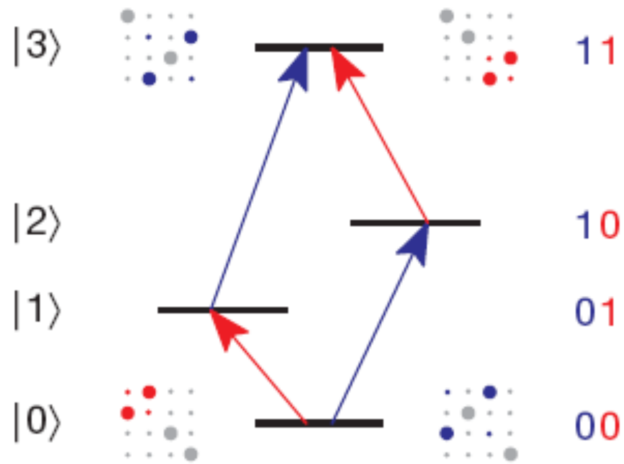
$$H = H_1 + H_2 + H_{12} = -\frac{1}{2}\left(\varepsilon_1\sigma_z^1 + \Delta_1\sigma_x^1 + \varepsilon_2\sigma_z^2 + \Delta_2\sigma_x^2\right) + J\sigma_z^1\sigma_z^2$$

Operation of the coupled-qubit device

Energy level diagram

- four resonance frequencies
- A resonant microwave pulse induces rotations in the computational basis

$$\boxed{0_C 0_T, 0_C 1_T, 1_C 0_T, 1_C 1_T}$$

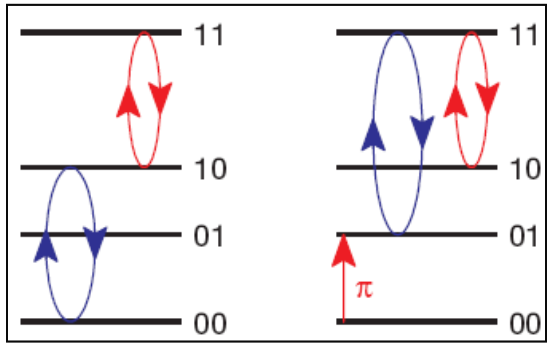


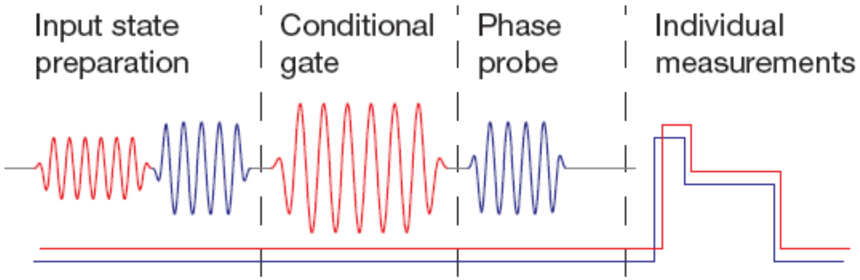
Sequence of operations

- Initial ground state $0_C 0_T$
- Preparation of input states

  1. $\frac{1}{\sqrt{2}}\left(|00\rangle + |10\rangle\right)$ 2. $\frac{1}{\sqrt{2}}\left(|01\rangle + |11\rangle\right)$
- Gate operation by applying a pulse
- Analysis of the resulting density matrix with probe pulses
- Simultaneous and independent determination of the two qubit state
- Repetition of N times ⟹ state counts

  $N_{00}, N_{01}, N_{10}, N_{11}$





Tunability and read-out

- Measured joint probabilities

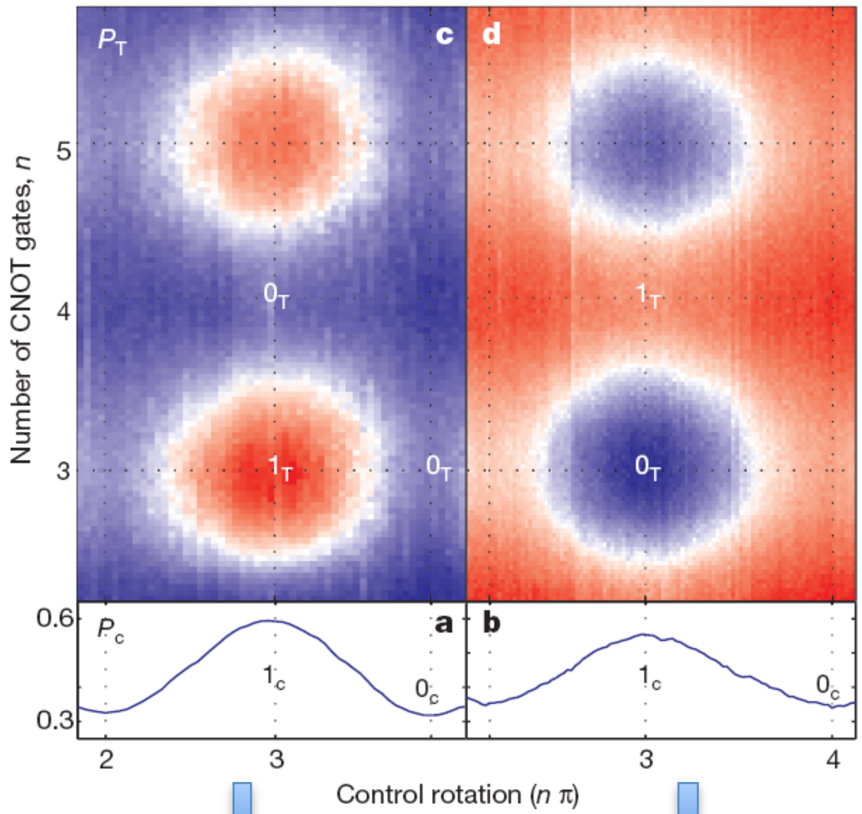
  $$P_{00}\,,\,P_{01}\,,\,P_{10}\,,\,P_{11}$$

  $$P_C = P_{10} + P_{11}$$

  $$P_T = P_{01} + P_{11}$$

- Odd numbers of π rotations and C-NOT gates flips the target qubit

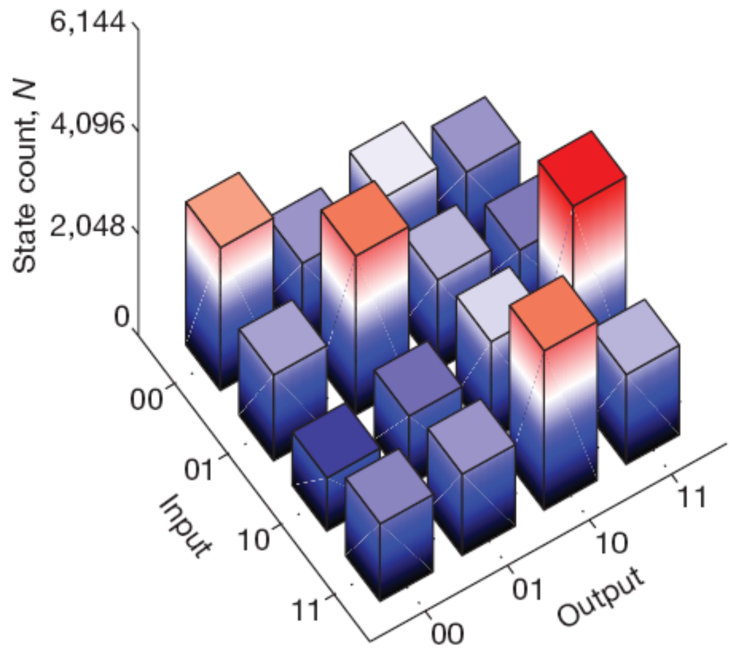
- It is a 1c-controlled gate

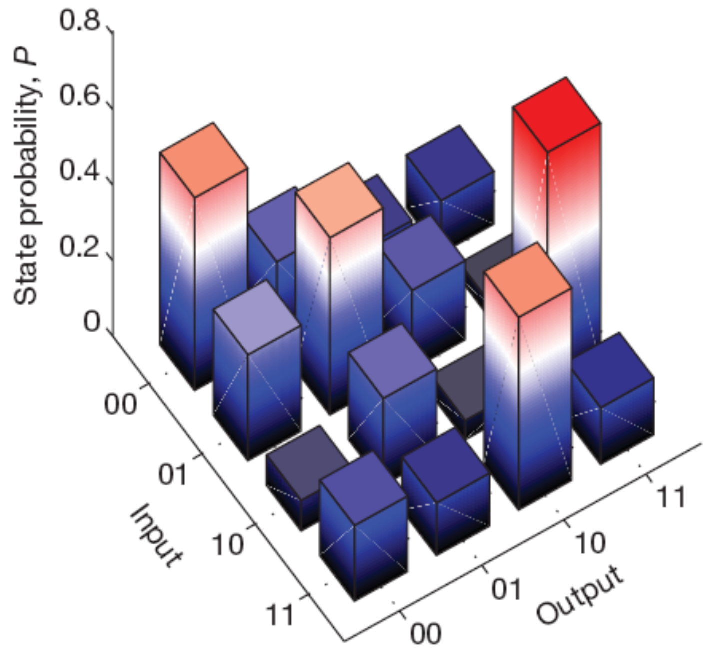


$$input:\frac{1}{\sqrt{2}}\left(|00\rangle+|10\rangle\right)$$

$$input:\frac{1}{\sqrt{2}}\left(|01\rangle+|11\rangle\right)$$

Truth table-Correction





- Input states $0_C 0_T, 0_C 1_T \Rightarrow$ remain unaffected

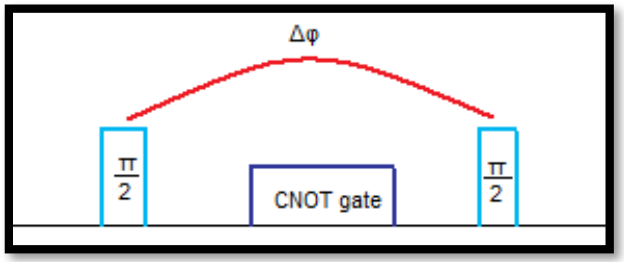
  $1_C 0_T, 1_C 1_T \Rightarrow$ target qubit inverted

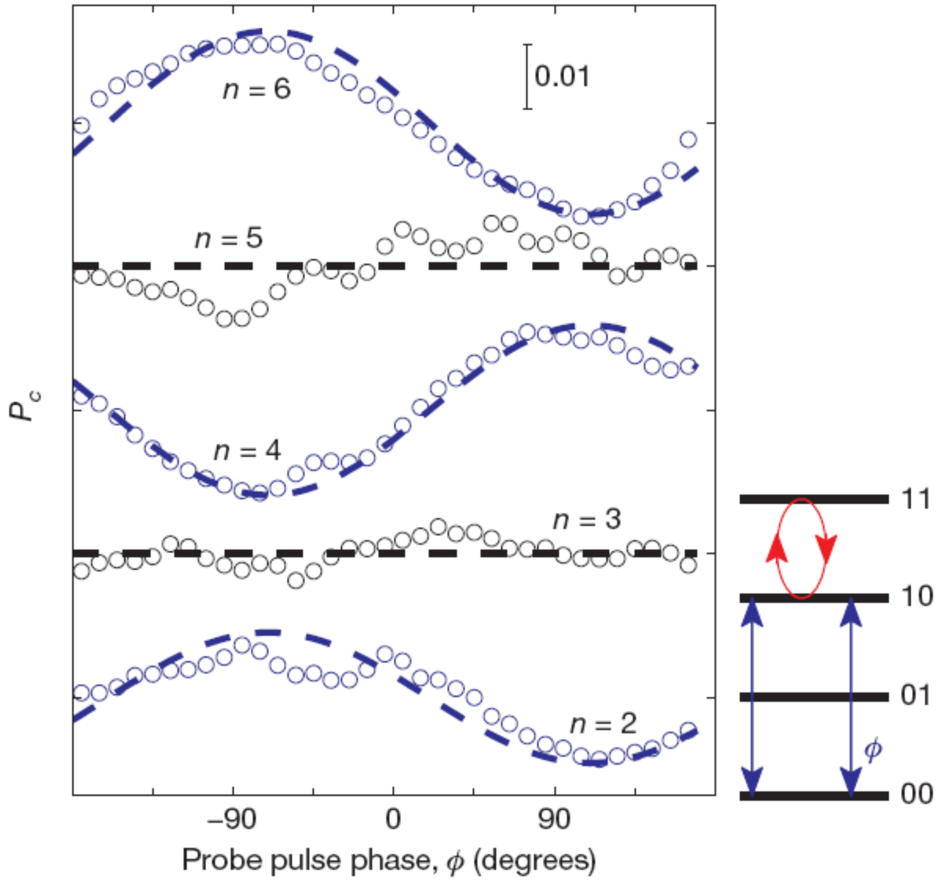
<u>Corrected truth table</u>

- Correction with conditional spectroscopy measurements
- New F=0.4

Phase Factor

- Ramsey-like interference experiment on n consecutive CNOT gates
- Starting at superspositions instead of starting at eigenstates
- Additional π/2 pulse after the gate with phase difference Δϕ to the one before the gate





- Even number of gates
  ➡ Phase gate

Conclusions

- Two different implementations of CNOT gate
- Main differences:

- Charge qubits
- Capacitive coupling
- Zero-controlled gate
- Simulated truth table
- Phase unknown

- Flux qubits
- Inductive coupling
- One-controlled gate
- Measured truth table
- Phase determination

→ Two qubit algorithms and solid-state qubit entaglement is possible

Summary-Outlook

- Superconducting qubits are among the most promising candidates for quantum computation

- Obstacles to overcome:
  - ⇨ increasing decoherence time
  - ⇨ improvement of read-out fidelity
  - ⇨ implementing error correction methods