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LETTERS

Demonstration of two-qubit algorithms with a superconducting quantum processor

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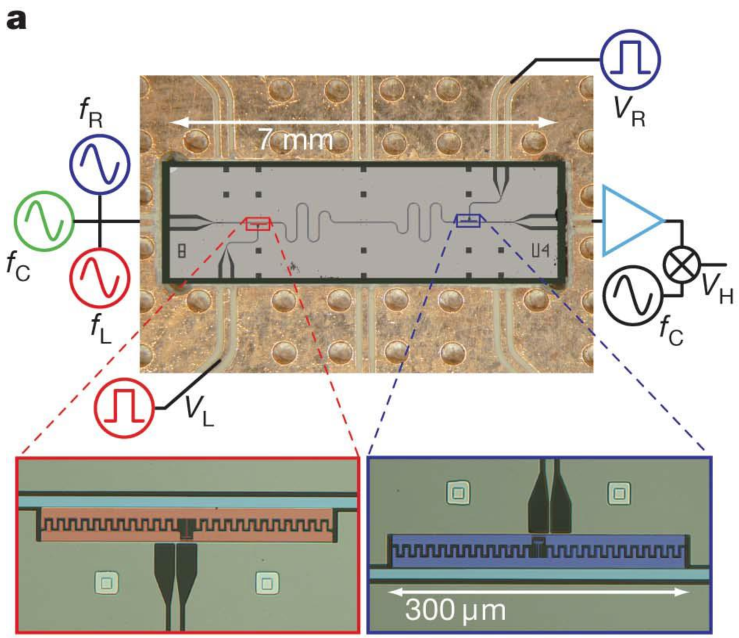
Tasks and challenges

- Requirements already achieved:
  - large coherence times
  - single-qubit gates with low error rates
  - two-qubit entanglement with good concurrence
  - readout with high fidelity

- Whats new in this paper:
  - combination of all these achievements in one device

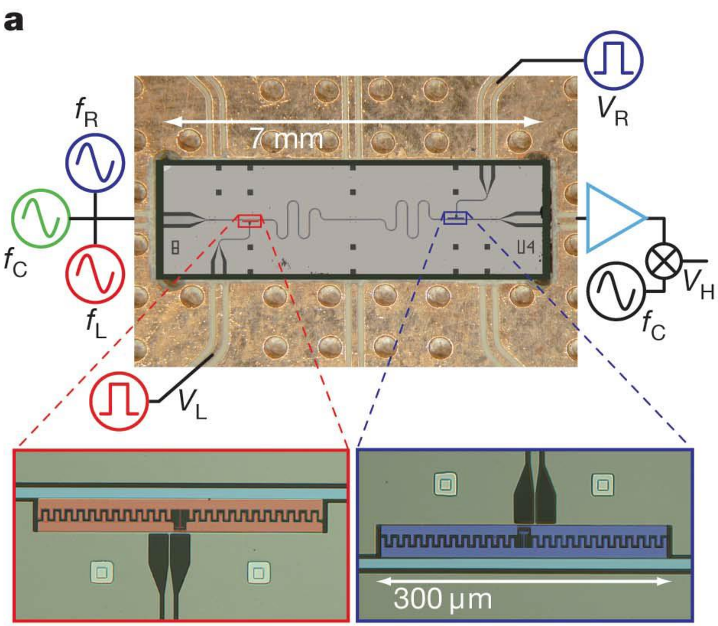
- Remaining challenges:
  - scalability

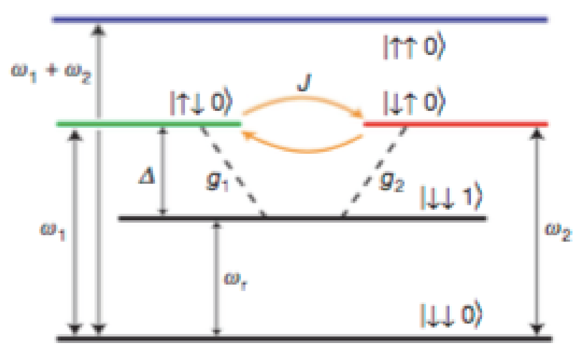
Device fabrication



- Sputtered NB film on corundum wafer
- Waveguide structures via optical lithography
- Transmon features patterned using:
  - electron-beam lithography
  - double-angle evaporation of Al
  - lift-off
- whole device cooled down to 13mK

Device structure



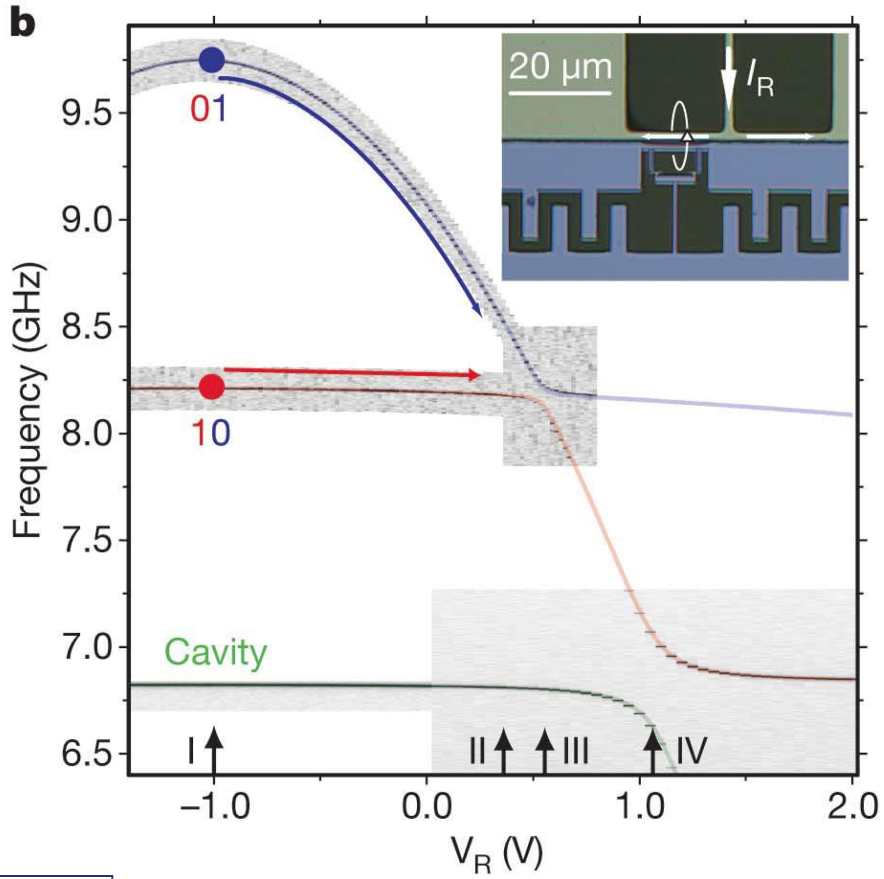


- quantum bus architecture
- cavity couples qubits via virtual photon exchange
- four-port superconducting device with two transmon qubits
- flux-bias lines that tune individual qubit frequencies → single-qubit gate
- pulsing qubit frequencies to an avoided crossing → two-qubit conditional phase gate
- local magnetic fields to tune qubit transition frequencies by many GHz

$$hf \approx \sqrt{8E_C E_J^{\max}|\cos(\pi\Phi/\Phi_0)|} - E_C$$

Single Qubit preparation

- Changing V_R
  - Flux change
- Single state preparation in point I
  - Large detuning in qbuit frequencies
- Computational Basis
  - 00, 01, 10 ,11



$$H = \omega_C a^\dagger a + \sum_{q\in\{L,R\}} \left(\sum_{j=0}^{N} \omega_{0j}^q |j\rangle_q \langle j|_q + (a + a^\dagger) \sum_{j,k=0}^{N} g_{jk}^q |j\rangle_q \langle k|_q \right)$$

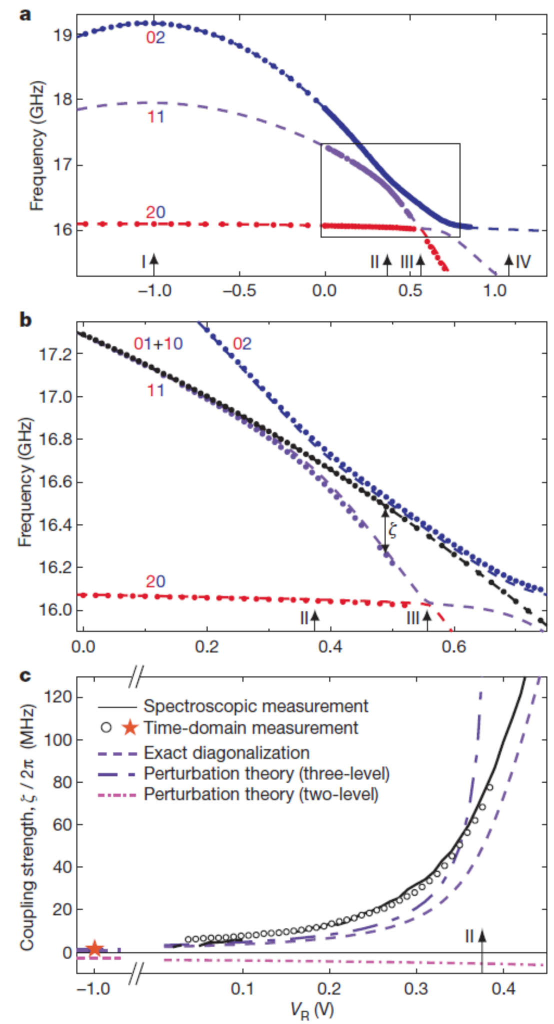
$$hf \approx \sqrt{8 E_C E_J^{\max} |\cos(\pi\Phi/\Phi_0)|} - E_C,$$

Two Qubit interaction

- Use a non computational state for two qubit rotation in point II
- Interaction can be tuned over two orders of magnitude

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\phi_{01}} & 0 & 0 \\ 0 & 0 & e^{i\phi_{10}} & 0 \\ 0 & 0 & 0 & e^{i\phi_{11}} \end{pmatrix}$$

$$\phi_{11} = \phi_{01} + \phi_{10} - \int \zeta(t)\mathrm{d}t.$$



The Readout Process

- Joint dispersive readout
  - Send frequency into resonator close to resonator frequency
  - Dispersive qubit resonator interaction→ three constant coefficients have approximately the same magnitude

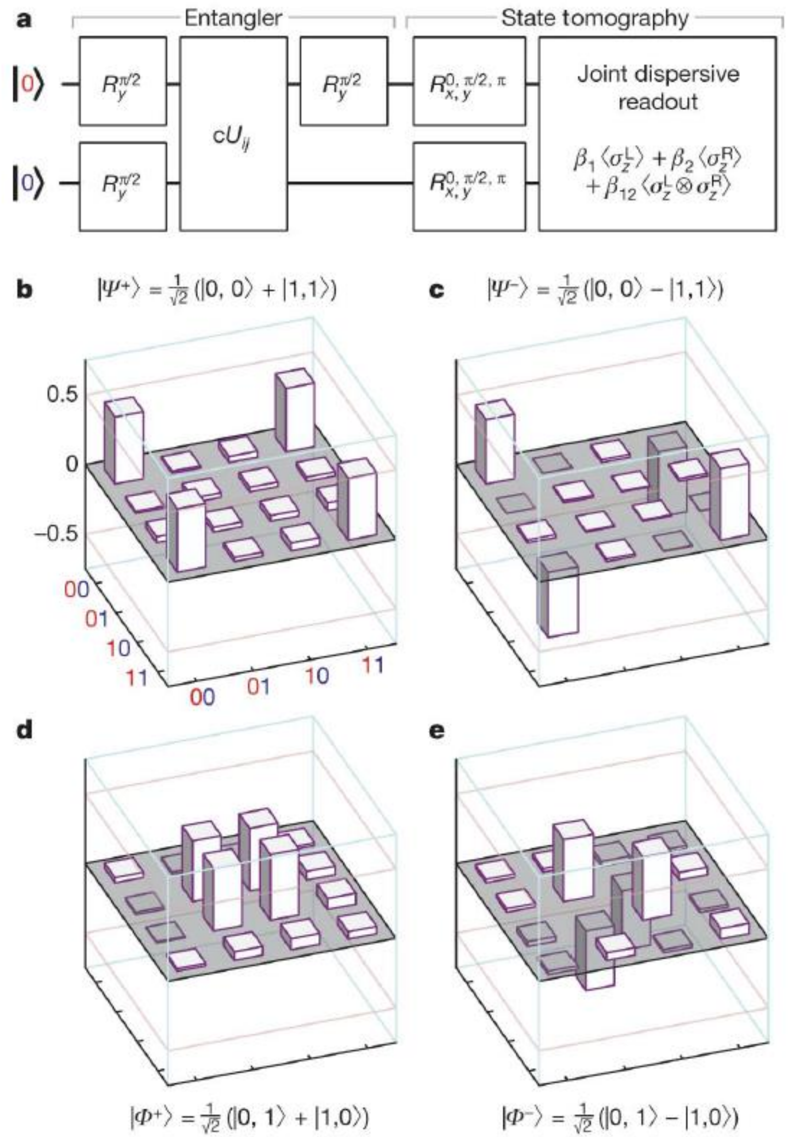
$$M = \beta_1 \sigma_z^{\mathrm{L}} + \beta_2 \sigma_z^{\mathrm{R}} + \beta_{12} \sigma_z^{\mathrm{L}} \otimes \sigma_z^{\mathrm{R}}$$

- State tomography
  - Make statistics of dispersive readout to reproduce the elements of the density matrix

  - In this paper 450’000 Data points

Bell state preparation:

- Concurrence : around 0.85
- Fidelty: upto 0.94



Algorithms - Preliminaries

- Quantum Gate:
  Unitary Transformation on 1 or n-qubits
- Hadamard-Gate:
  Transformation X $\leftrightarrow$ Z basis
  Used to create superposition states
- Quantum Parallelism:
  Evaluation of f(x) for various values of x
  Using superposition

Grover Algorithm

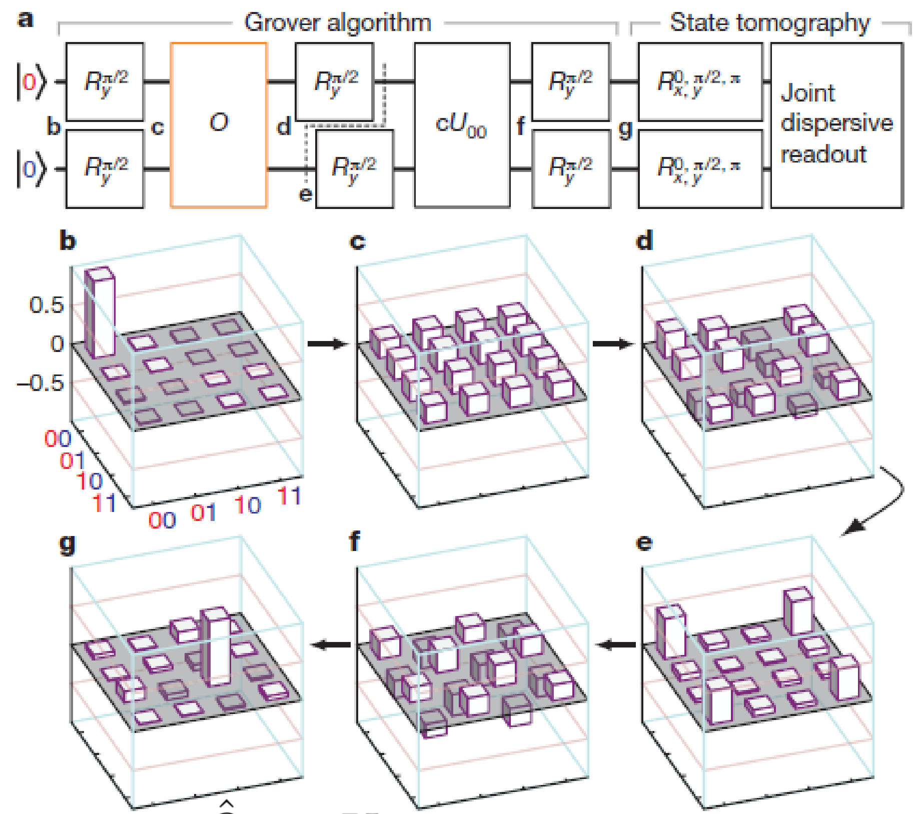
- Aim: search element x_0 in list
- Classically: $O(N)$
- QM: $O(\sqrt{N})$

- Input: $x \in \{00, 01, 10, 11\}$
- Output:

$$f(x) = \begin{cases} 1 & x = x_0 \\ 0 & \text{else} \end{cases}$$

- Single run:

$$\hat{O}\,|x\rangle = (-1)^{f(x)}\,|x\rangle = cU_{ij}\,|x\rangle$$



$$\hat{O} = cU_{10}$$

a. 1 iteration of Grover/ b. Input $|00\rangle$/ c. Superposition/ d. Oracle/ e. $R_y^{\pi/2}$ on Q_R / f. $R_y^{\pi/2}$ on Q_L creates $|\Psi^+\rangle$ /g. Output state

Results - Grover

Table 1 | Summary of algorithmic performance

Element		Grover search oracle*			
		f_{00}	f_{01}	f_{10}	f_{11}
$\langle 0,0\|\rho\|0,0\rangle$	Ideal	1	0	0	0
	Measured	0.81(1)	0.08(1)	0.07(2)	0.065(7)
$\langle 0,1\|\rho\|0,1\rangle$	Ideal	0	1	0	0
	Measured	0.066(7)	0.802(9)	0.05(1)	0.054(8)
$\langle 1,0\|\rho\|1,0\rangle$	Ideal	0	0	1	0
	Measured	0.08(1)	0.05(1)	0.82(2)	0.07(1)
$\langle 1,1\|\rho\|1,1\rangle$	Ideal	0	0	0	1
	Measured	0.05(2)	0.07(1)	0.06(1)	0.81(1)

Fidelity of the reconstructed output states

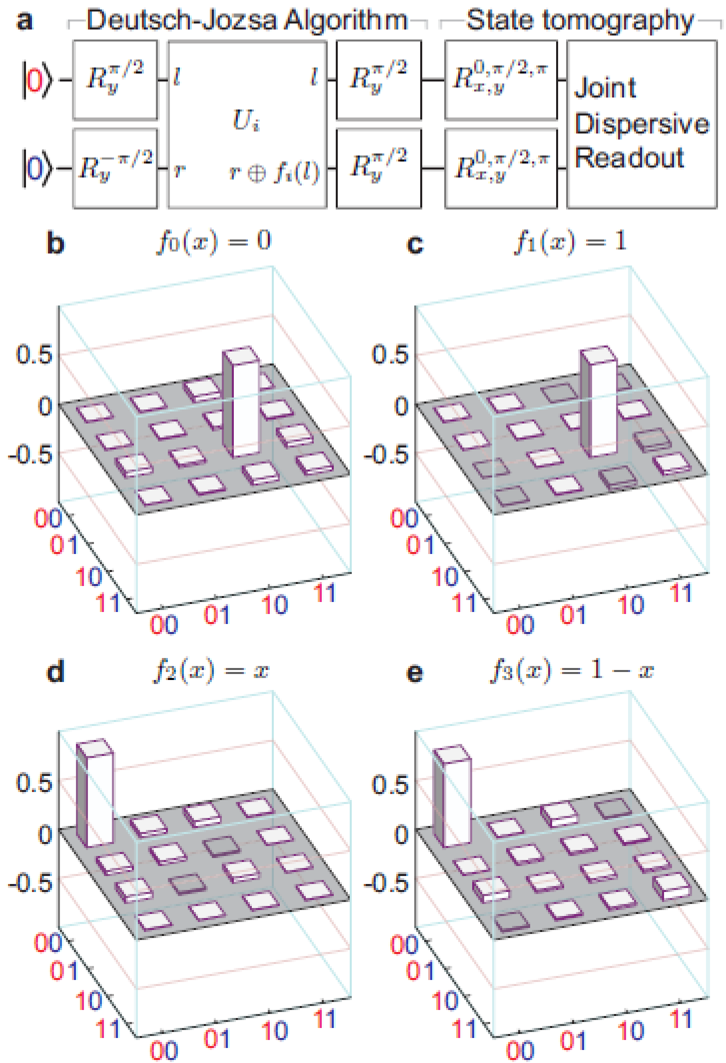
Uncertainties are based on 10 repititions

Deutsch-Josza Algorithm

- Aim: Constant or Balanced?
- Classically: $\frac{N}{2}+1$ calls of $f(x)$
- QM: single call of $f(x)$
- Input: $x \in \{00, 01, 10, 11\}$
- Output: $f(x) = \begin{cases} \text{constant} \\ \text{balanced} \end{cases}$

$f(x)$: 1 input BIT → 1 output BIT

- $U_i \left|l\right\rangle \left|r\right\rangle = \left|l\right\rangle \left|r \oplus f(l)\right\rangle$



a. Gate sequence/ Constant: b. $f_0(x) = 0$ / c. $f_1(x) = 1$
Balanced: d. $f_2(x) = x$ / e. $f_3(x) = 1 - x$

Results – Deutsch-Josza

Table 1 | Summary of algorithmic performance

Element		Deutsch–Jozsa function†			
		f_0	f_1	f_2	f_3
$\langle 0,0 \vert \rho \vert 0,0 \rangle$	Ideal	0	0	1	1
	Measured	0.010(3)	0.014(5)	0.909(6)	0.841(9)
$\langle 0,1 \vert \rho \vert 0,1 \rangle$	Ideal	0	0	0	0
	Measured	0.012(4)	0.008(4)	0.031(8)	0.04(2)
$\langle 1,0 \vert \rho \vert 1,0 \rangle$	Ideal	1	1	0	0
	Measured	0.93(1)	0.93(1)	0.05(1)	0.04(1)
$\langle 1,1 \vert \rho \vert 1,1 \rangle$	Ideal	0	0	0	0
	Measured	0.05(1)	0.04(1)	0.012(9)	0.07(2)

Fidelity of the reconstructed output states

Uncertainties are based on 8 repititions

Achievements & Outlook

- Local flux control
- Joint dispersive readout in cQED
- On-demand-Generation of entangled Qubits

- Extension to $n \geq 2$ qubits by $\sigma_x \otimes \sigma_x$ between nearest frequency neighbour interactions

➔ GHZ states
➔ Simple error correction

ETH zürich

Thank you!