Superconducting qubits
State-of-the-art and where do we go from here?

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Quantum computing: What's the point?

Computations using quantum bits (performed in a highly specific way) can provide computational speedups (for certain problems).

**P**
- Efficiently solvable and checkable on classical computer

**NP**
- Efficiently checkable (but **not** efficiently solvable) on classical computer

**BQP**
- Efficiently solvable and checkable on a quantum computer

Quantum computers fundamentally change what is *computationally feasible*.

**EXAMPLES**
- Is 179,424,673 a prime number?
- What are the prime factors of 179,424,673?
Superconducting quantum computers: What are they?

Electrical circuits fabricated using superconducting materials and patterned with nano- and microlithography techniques:

- *Quantum* properties can be changed, just by changing electrical pattern
- *Exceedingly* reproducible -> can be prototyped and optimized very quickly

Figure from MK et al, arXiv:2001.08838
Superconducting quantum computing: What do they look like?

We install the device in a cryogenic measurement configuration. We correctly assign the ancilla measurement outcome based on the probabilistic encoding scheme, where we initialize the data qubits to the correct parity assignment probability. This arises due to the overlap between the measured probabilities and the ideal distribution of bitstrings. For each stabilizer, the other ancilla qubits and unused data qubits are left in the ground state. We measure the multi-qubit stabilizers using the ancilla to measure the multi-qubit stabilizers using the ancilla. It is, thus, critical to directly verify the ability to measure the multi-qubit stabilizers using the ancilla.

We designed a quantum processor named 'Sycamore' which consists of an array of 54 transmon qubits, where each qubit is tunably coupled to four nearest neighbours, in a rectangular lattice. The structure and therefore allow for limited guarantees of computational superiority against state-of-the-art classical computers in the task of sampling the output distribution.

For each stabilizer, we collect the measured bitstrings and produce a distribution of probabilities. Intuitively, the observed bitstrings are correlated with how often we verify that the quantum processor is working properly using a method called cross-entropy benchmarking (see also DQC Conference). We design the circuits to entangle a set of quantum bits and produce a given product state and perform one error measurement. It is, thus, critical to directly verify the ability to perform one error measurement.

In a superconducting circuit, conduction electrons condense into a macroscopic quantum state, such that currents and voltages behave classically. This allows us to use classical computing to quickly tune the qubit–qubit coupling from completely off to 40 GHz.

We verify that the quantum processor is working properly using a cross-entropy benchmarking method called cross-entropy benchmarking. As shown in Fig. 13, we observe bitstrings that are correlated with how often we verify that the quantum processor is working properly using a method called cross-entropy benchmarking (see also the DQC Conference). We design the circuits to entangle a set of quantum bits and produce a given product state and perform one error measurement. It is, thus, critical to directly verify the ability to perform one error measurement.
Late last year a superconducting quantum computer outperformed the world's largest classical supercomputer:

Using 53 superconducting qubits (of the transmon variety), the Google Quantum AI team demonstrated a calculation in ~200s that is expected to take between ~a few weeks and up to ~10,000 years on the Summit supercomputer.
**Transmon qubit:**

The transmon qubit is a type of superconducting qubit that is largely insensitive to charge, resulting in improved reproducibility and coherence times. This makes it a viable candidate for implementing medium- and large-scale quantum computation.

**INTRODUCTION**

The ability to control individual quantum degrees of freedom and their interactions unlocks the capability to perform quantum coherent computation. This in turn imparts the possibility to perform certain computational tasks and quantum simulations that are outside the reach of modern supercomputers. Superconducting qubits—collective excitations in superconducting circuits—are currently one of the leading approaches for realizing quantum logic elements and quantum coherent interactions with sufficiently high controllability and low noise.

In 2014, the first controlled qubit–qubit interaction with fidelities greater than 0.99 in multi-qubit systems was demonstrated with the transmon qubit variant of superconducting qubits, and since then, multiple controlled two-qubit interactions have been demonstrated with similarly high fidelities. Even though the two-qubit gate fidelity in multi-qubit systems is a limited metric for evaluating the maturity of a quantum computing technology, it implies a high degree of control of all aspects of the quantum processor and indicates the state of play: Superconducting qubits are well positioned to be a platform for demonstrating interesting noisy intermediate-scale quantum (NISQ) computing protocols outside the reach of classical computers and first realizations of operations on multiple logical error-corrected qubits.

In Figure 1, we show two major tracks being pursued in parallel in the community. The left track shows the progression toward building a fault-tolerant quantum computer, capable of running an arbitrarily long computation, to arbitrary precision. Since 2012–2013, the improvements to classical control, physical qubits, and native gates have been significant.

The right track is the NISQ approach, where highly optimized quantum algorithms and quantum simulations, which typically take into account details of the quantum processor, can be executed without generalized quantum error correction procedures. The two tracks are pursued in parallel in many academic, government, and industrial laboratories.
Superconducting quantum computing: Where are we going?

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**Table 1** State-of-the-art high-fidelity, two-qubit gates in superconducting qubits

<table>
<thead>
<tr>
<th>Acronym*</th>
<th>Layout‡</th>
<th>First demonstration [Year]</th>
<th>Highest fidelity [Year]</th>
<th>Gate time</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZ (ad.)</td>
<td>T–T</td>
<td>DiCarlo et al. (72) [2009]</td>
<td>∼99.4%* Barend et al. (3) [2014]</td>
<td>40 ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>∼99.7%* Kjaergaard et al. (73) [2020]</td>
<td>60 ns</td>
</tr>
<tr>
<td>√SWAP</td>
<td>T–T</td>
<td>Neeley et al. (81)* [2010]</td>
<td>90%* Dewes et al. (74) [2014]</td>
<td>31 ns</td>
</tr>
<tr>
<td>CR</td>
<td>F–F</td>
<td>Chow et al. (75)* [2011]</td>
<td>99.1%* Sheldon et al. (5) [2016]</td>
<td>160 ns</td>
</tr>
<tr>
<td>√BSWAP</td>
<td>F–F</td>
<td>Poletto et al. (76) [2012]</td>
<td>86%* Poletto et al. (76) [2012]</td>
<td>800 ns</td>
</tr>
<tr>
<td>MAP</td>
<td>F–F</td>
<td>Chow et al. (77) [2013]</td>
<td>87.2%* Chow et al. (75) [2011]</td>
<td>510 ns</td>
</tr>
<tr>
<td>CZ (ad.)</td>
<td>T–(T)–T</td>
<td>Chen et al. (55) [2014]</td>
<td>99.0%* Chen et al. (55) [2014]</td>
<td>30 ns</td>
</tr>
<tr>
<td>RI</td>
<td>3D F</td>
<td>Paik et al. (78) [2016]</td>
<td>98.5%* Paik et al. (78) [2016]</td>
<td>413 ns</td>
</tr>
<tr>
<td>√SWAP</td>
<td>F–(T)–F</td>
<td>McKay et al. (79) [2016]</td>
<td>98.2%* McKay et al. (79) [2016]</td>
<td>185 ns</td>
</tr>
<tr>
<td>CZ (ad.)</td>
<td>T–F</td>
<td>Caldwell et al. (80) [2018]</td>
<td>99.2%* Hong et al. (6) [2019]</td>
<td>176 ns</td>
</tr>
<tr>
<td>CNOT_L</td>
<td>BEQ–BEQ</td>
<td>Rosenblum et al. (13) [2018]</td>
<td>~99%* Rosenblum et al. (13) [2018]</td>
<td>190 ns</td>
</tr>
<tr>
<td>CNOT_T.L</td>
<td>BEQ–BEQ</td>
<td>Chou et al. (82) [2018]</td>
<td>79%* Chou et al. (82) [2018]</td>
<td>4.6 µs</td>
</tr>
</tbody>
</table>

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**Operation count** = \( \frac{T_2 \text{ lifetime}}{\text{gate time}} \)

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* 'Fidelity' is approximately the 'quality' of the quantum operation that generates entanglement in the quantum processor. **Key metric.**

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‘Lifetime’ is approximately the time for which the qubit ‘retains its memory’. **Key metric.**
Transmon qubit: an ac actively ly tuned Cooper-pair box that is largely insensitive to charge, resulting in improved reproducibility and coherence times.

1. INTRODUCTION

The ability to control individual quantum degrees of freedom and their interactions unlocks the capability to perform quantum coherent computation. This in turn imparts the possibility to perform certain computational tasks and quantum simulations that are outside the reach of modern supercomputers (1, 2). Superconducting qubits—collective excitations in superconducting circuits—are currently one of the leading approaches for realizing quantum logic elements and quantum coherent interactions with sufficiently high controllability and low noise to be a viable candidate for implementing medium- and large-scale quantum computation.

In 2014, the first controlled qubit–qubit interaction with fidelities greater than 0.99 in multi-qubit systems was demonstrated (3) with the transmon qubit (4) variant of superconducting qubits, and since then, multiple controlled two-qubit interactions have been demonstrated with similarly high fidelities (see, e.g., 5, 6). Even though the two-qubit gate fidelity in multiqubit systems is a limited metric for evaluating the maturity of a quantum computing technology, it implies a high degree of control of all aspects of the quantum processor and indicates the state of play: Superconducting qubits are well positioned to be a platform for demonstrating interesting noisy intermediate-scale quantum (NISQ) computing (7) protocols outside the reach of classical computers and first realizations of operations on multiple logical error-corrected qubits (8, 9).

In Figure 1, we show two major tracks being pursued in parallel in the community. The left track (see, e.g., 9, 10) shows the progression toward building a fault-tolerant quantum computer, capable of running an arbitrarily long computation, to arbitrary precision. Since 2012–2013, the improvements to classical control, improvements to physical qubits, improvements to native gates, improvements to qubit readout, and improvements to qubit readout have contributed to the state-of-the-art demonstrations. The right track is the NISQ approach (see Reference 7), where highly optimized quantum algorithms and quantum simulations, which typically take into account details of the quantum processor, can be executed without generalized quantum error correction procedures. The two tracks are pursued in parallel in many academic, government, and industrial laboratories. Abbreviation: NISQ, noisy intermediate-scale quantum.
Superconducting quantum computing: State-of-the-art experiments (a selection)

Fault-tolerant quantum computers
- General purpose fault-tolerant quantum computation
- Algorithms on multiple logical qubits
- Operations on single logical qubits
- Logical qubits with improved properties over physical qubits

Noisy intermediate-scale quantum computers
- Improved native gate set
- Noise mitigation
- Device connectivity

Tailored quantum computations outside the reach of classical computing

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**Figure 1**

*Ancilla state* *Ancilla event* *Logical operation*  
| f | No error | S(f) |  
| g | Relaxation | S(g) |  
| i | Dephasing |  |

*Start*  
| X |  
| Y |  
| Z |  

*Probability correct*  
- RB  
- IRB (S)  
- IRB (SINC)  


Programming a quantum computer with quantum instructions

"CODE <=> DATA"
Homoiconicity
Restoring programming parity to quantum computers

“CODE <=> DATA”

CODE: CLASSICAL
DATA: CLASSICAL

Classical instruction set for classical computing

Instruction set

\[ f = 00011011011... \]

Control layer

\[ f = \]

Algorithm

\[ 110... \]

...\[ f \]

\[ f \]

\[ 011 \]

CODE: CLASSICAL
DATA: QUANTUM

Classical instruction set for quantum computing

Single-qubit

\[ 0110 \]

\[ X_{\pi/2} \]

\[ \psi - U - e^{-iH(0110)t}\psi \]

Multi-qubit

\[ 1101100100110... \]

\[ \psi - U - e^{-iH(110...)t}\psi \]

Quantum instruction set for quantum computing

Single-qubit

\[ \rho_1 \in \mathbb{C}^{2 \times 2} \]

\[ \rho_n \in \mathbb{C}^{2^n \times 2^n} \]

\[ \rho_1 \]

\[ \rho_1 \]

\[ \rho_n \]

\[ \rho_n \]

\[ \psi - DME_N - e^{-i\rho_n}\psi \]

Density Matrix Exponentiation

Multi-qubit

Rest of this talk

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Density Matrix Exponentiation (DME): Operating principle

DME is a fixed protocol that implements an operation only dependent on the setting of the instruction state $\rho$:

$$\rho \otimes N \xrightarrow{\text{DME}_N} e^{-i\rho \theta} + O(\theta^2/N)$$

($\theta$ an angle)

Seth Lloyd *et al*, Nat. Phys. 2014

**Conceptually**

Density Matrix Exponentiation allows us to load a program into a state (‘instruction state’ or ‘quantum program’, $\rho$) and execute that quantum program on another quantum system.
Programming with quantum states

\[ \sigma_{in} = \frac{1}{\sqrt{2}} (|+y\rangle + |+y\rangle) \quad \text{DME}(|+x\rangle \langle +x|, 4, \pi/2) \approx \sigma_{in} = |+y\rangle + |+y\rangle \quad R_{x}(\pi/2) \]

Instruction state
Total angle \( \theta \)
Number of steps \( N \)
Programming with quantum states

\[
\sigma_{\text{in}} = |+y\rangle\langle+y| - \text{DME}(|+x\rangle\langle+x|, 4, \frac{\pi}{2}) \approx |+y\rangle\langle+y| R_x(\frac{\pi}{2})
\]

Target qubit: \( \sigma_{\text{in}} = |+y\rangle\langle+y| \)

Instruction qubit: \( \rho_{\text{in}} = |+x\rangle\langle+x| \)

\[
\delta = \frac{\pi}{2^4}
\]

\[
\text{SQM}_x - \text{SQM}_x - \text{SQM}_x - \text{SQM}_x
\]

- Simulated Quantum Measurement Gate, A. Greene, MK, et al. (in preparation, 2020)

Single qubit DME

Instruction state: \( \rho = |+x\rangle\langle+x| : \)

\[
\rho = |+x\rangle\langle+x| = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} = \frac{1}{2} (\mathbb{1} + \sigma_x)
\]

Input to density matrix exponentiation:

\[
e^{-i\rho\theta} = e^{-i\frac{\theta}{2}(\mathbb{1} + \sigma_x)} \approx e^{-i\sigma_x \frac{\theta}{2}} = R_x(\theta)
\]

The setting of the instruction qubit “instructs” axis to rotate the target qubit about
Why are quantum instructions interesting?

DME is exceedingly efficient for generating quantum instructions

**Exponential** reduction in resource requirements over any tomographic strategy
(Kimmel et al, npj QI 2017)

**Algorithm runtime** scales only logarithmically with dimension of instruction state

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**Quantum principal component analysis**


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**Efficient measurements of entanglement spectra**

Pichler et al, PRX, 6 041033 (2016)

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**Sample optimal Hamiltonian simulation**

Kimmel et al, npj QI, 3 13 (2017)

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**Quantum semi-definite programming**


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**Universal quantum emulation**

Programming parity can be restored to quantum computing using the **Density Matrix Exponentiation algorithm**

We demonstrated a proof of principle version of this algorithm using superconducting qubits, and a novel gate construction for approximately resetting a known state.

Superconducting quantum computing in Denmark

Quantum algorithms and simulation

4-level superconducting transmon qubit
Capacitive coupling
Hexagonal super lattice

Multi-photon bound state
Chiral waveguide
Quantum program stored in $U$
Quantum emulation of $U$

Quantum fault tolerance

Error detection qubit
Data qubits

On-chip quantum communication protocols

Alice Noisy channel Bob

Want to study foundational problems and applications of superconducting qubits to quantum information processing? We are looking for students and postdocs! Let me know at mkjaergaard@nbi.ku.dk