Superconducting Approaches
to
Quantum Information Processing
and
Quantum Computing

A Quantum Information Science and Technology Roadmap

Part 1: Quantum Computation

Section 6.7

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List of Acronyms and Abbreviations

dc	direct current	rf	radio frequency
GHz	gigahertz	SET	single-electron transistor
GHZ	Greenberger, Horne, and Zeilinger	SFQ	single flux quantum
mK	millikelvin	SPD	single-photon detector
NMR	nuclear magnetic resonance	SQUID	superconducting quantum interference device
QC	quantum computing/computation	TEP	Technology Experts Panel

1.0 Groups Pursuing This Approach

Note: This document constitutes the most recent draft of the Superconducting detailed summary in the process of developing a roadmap for achieving quantum computation (QC). Please submit any revisions to this detailed summary to Todd Heinrichs (tdh@lanl.gov) who will forward them to the relevant Technology Experts panel (TEP) member. With your input can we improve this roadmap as a guidance tool for the continued development of QC research.

Table 1-1
Approaches to Superconducting QC Research

Research Leader(s)	Research Location	Research Focus
Averin & Likharev	StonyBrook	theory of superconducting qubits
Berggren	MIT	flux-based qubits
Bruder	Basel	theory of superconducting qubits
Buisson	Grenoble	charge-based qubits
Choi	Korea	theory of superconducting qubits
Clarke	Berkeley	flux-based qubits
Cosmelli	Rome	flux-based qubits
Delsing	Chalmers	charge-based qubits
Devoret	Yale	charge-based qubits
Echternach	JPL	charge-based qubits
Esteve	Saclay	charge-based qubits
Falci	Catania	theory of superconducting qubits
Fazio	Pisa	theory of superconducting qubits
Feldman/Bocko	Rochester	flux-based qubits
Han	Kansas	flux-based qubits AND single-junction phase-based qubits
Koch	IBM	flux-based qubits
Kouwenhoven	Delft	charge-based qubits
Ladizinsky	TRW	flux-based qubits
Levitov	MIT	theory of superconducting qubits
Likharev	StonyBrook	charge-based qubits
Lloyd	MIT	theory of superconducting qubits
Lukens, Likharev, & Semenov	StonyBrook	flux-based qubits
Manheimer	LPS	charge-based qubits
Martinis	UCSB	single-junction phase-based qubits
Mooij	Delft	flux-based qubits
Nakamura	NEC	charge-based qubits

Table 1-1
Approaches to Superconducting QC Research

Research Leader(s)	Research Location	Research Focus
Nori	Michigan and Riken	theory of superconducting qubits
Oliver, Gouker	Lincoln Lab	flux-based qubits
Orlando	MIT	flux-based qubits
Schoelkopf	Yale	charge-based qubits
Schön, Shnirmann, & Makhlin	Karlsruhe	theory of superconducting qubits
Silvestrini	Naples	flux-based qubits
Simmonds	NIST	phase-based qubits
Tanaka	NTT	flux-based qubits
Ustinov	Erlangen	flux-based qubits
van Harlingen	Illinois	flux-based qubits
Wellstood, Anderson, & Lobb	Maryland	flux-based qubits AND single-junction phase-based qubits
Wilhelm	Munich	theory of superconducting qubits

2.0 Background and Perspective

The qubits are superconducting circuits made with Josephson junctions and operating at millikelvin (mK) temperatures. The information is stored in either the charge on a nanoscale superconducting island, the flux or phase drop in a circulating current, or in the energy levels in a single junction [1]. The interactions are either capacitive for charge-based circuits or inductive for flux- or phase-based circuits. Because these are electrical circuits, other electrical coupling elements are possible, such as tunnel junctions, transformers, single-electron transistors (SETs), etc.

The typical energy-level splitting between the qubit states varies between 1 and 10 GHz.

Clock speeds are estimated to be of the order of a nanosecond (this is the minimum time for a one-qubit rotation). The qubits are prepared in their initial state by cooling the system to their ground state. Then radio frequency (rf) electromagnetic pulses are used to manipulate the qubits to perform quantum operations. The manipulation of the superconducting qubits can be controlled by on-chip, ultrafast superconducting circuitry. For example, simple single-flux-quantum (SFQ) circuitry can operate at speeds up to 700 GHz with small power dissipation. There is a broad diversity of measurement options appropriate to different speeds and measurement bases. Most measurement schemes are based on superconducting quantum interference device (SQUID) magnetometers, SET electrometers, or switching of Josephson junctions.

3.0 Summary of Superconducting QC: The DiVincenzo Criteria

Note: For the five DiVincenzo QC criteria and the two DiVincenzo QC networkability criteria (numbers six and seven in this section), the symbols used have the following meanings:

a) = a potentially viable approach has achieved sufficient proof of principle;

b) = a potentially viable approach has been proposed, but there has not been sufficient proof of principle; and

c) = no viable approach is known.

1. A scalable physical system with well-characterized qubits
   - 1.1 The existence of two quantum states has been demonstrated experimentally.
     - 1.1.1 Charge states [2,3]
     - 1.1.2 Flux states in rf SQUID [4], persistent-current qubit [5], and an asymmetric direct current (dc) SQUID and fluxon qubits [6]
     - 1.1.3 Phase states in a single junction [7,8]
   - 1.2 Rabi oscillations between the two-qubit states
     - 1.2.1 Single junction [7,8]
     - 1.2.2 Charge states [2,3]
     - 1.2.3 Flux-based qubit [9]
   - 1.3 Ramsey Fringe experiments in hybrid qubits [3]
   - 1.4 No fundamental physical limits to scaling are currently known (note that few-qubit scaling vs many-qubit scaling will have very different challenges).
2. The ability to initialize the state of the qubits to a simple fiducial state
   - 2.1 The system is cooled to place the qubits in their ground states.
     - 2.1.1 Initial experiments suggest this can be done >90% [8].
3. Long (relative) decoherence times, much longer than the gate-operation time
   - 3.1 Calculations suggest the relaxation times are of the order of milliseconds or greater [1,10].
   - 3.2 Experimental measurements show at present a lower bound of about 1–10 μs for the relaxation time, and 0.1–0.5 μs for the dephasing time [2,3,7–9,11].
   - 3.3 Charge, flux, and critical-current noise are probably a technological and materials-processing problem [2,3,7–9,11].
   - 3.4 The nonresonant upper levels: in principle the effects of these levels can be compensated by a pulse sequence which allows the system to act as an effective two-level system [12].
   - 3.5 Experiments have demonstrated about a thousand gate operations prior to decoherence [3].

4. A universal set of quantum gates
   4.1 Many different schemes have been proposed for a universal set of two-level systems for gates in superconducting qubits. Most schemes are based on an NMR-like approach of using pulses of microwave radiation to perform qubit operations. In addition, nonadiabatic switching has been used to manipulate a single superconducting qubit [1].
   4.2 Parallel operations are possible in principle.

5. A qubit-specific measurement capability
   5.1. There is a broad diversity of measurement options appropriate to different speeds and measurement bases.
      5.1.1 RF-sets and SET-electrometers are used for charge states [13].
      5.1.2 SQUIDs are used to readout flux states, either by measuring its switching current modulation or by measuring its inductance [4,5,14,15,16].
      5.1.3 In the phase qubit, the switching current is measured [7,8].
      5.1.4 In hybrid circuits, the qubit and readout can be of different types. However, additional theoretical work is needed to build a testable, phenomenological model to optimize the measurement process [3].

6. The ability to interconvert stationary and flying qubits
   6.1 An optical cavity interacting with a flying qubit has been suggested.

7. The ability to faithfully transmit flying qubits between specified locations
   7.1 A superconducting transmission line has been suggested.

4.0 What Has Been Accomplished

Note: For the status of the metrics of QC described in this section, the symbols used have the following meanings:

a) = sufficient experimental demonstration;

b) = preliminary experimental demonstration, but further experimental work is required; and

c) = no experimental demonstration.

1. Creation of a qubit
   1.1 Demonstrate preparation and readout of both qubit states [2,4,5,7,8].

2. Single-qubit operations
   2.1 Demonstrate Rabi flops of a qubit.
   2.2 Demonstrate decoherence times much longer than Rabi oscillation period [3,7–9,11].
   2.3 Demonstrate control of both degrees of freedom on the Bloch sphere.

3. Two-qubit operations
   - 3.1 Implement coherent two-qubit quantum logic operations [17].
   - 3.2 Produce and characterize Bell states.
   - 3.3 Demonstrate decoherence times much longer than two-qubit gate times [17].
   - 3.4 Demonstrate quantum state and process tomography for two qubits.
   - 3.5 Demonstrate a two-qubit decoherence-free subspace (DFS).
   - 3.6 Demonstrate a two-qubit quantum algorithm.

4. Operations on 3–10 physical qubits
   - 4.1 Produce a Greenberger, Horne, & Zeilinger (GHZ) state of three physical qubits.
   - 4.2 Produce maximally entangled states of four and more physical qubits.
   - 4.3 Quantum state and process tomography.
   - 4.4 Demonstrate decoherence-free subspaces.
   - 4.5 Demonstrate the transfer of quantum information (e.g., teleportation, entanglement swapping, multiple SWAP operations, etc.) between physical qubits.
   - 4.6 Demonstrate quantum error-correcting codes.
   - 4.7 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza).
   - 4.8 Demonstrate quantum logic operations with fault-tolerant precision.

5. Operations on one logical qubit
   - 5.1 Create a single logical qubit and "keep it alive" using repetitive error correction.
   - 5.2 Demonstrate fault-tolerant quantum control of a single logical qubit.

6. Operations on two logical qubits
   - 6.1 Implement two-logical-qubit operations.
   - 6.2 Produce two-logical-qubit Bell states.
   - 6.3 Demonstrate fault-tolerant two-logical-qubit operations.

7. Operations on 3–logical qubits
   - 7.1 Produce a GHZ state of three logical qubits.
   - 7.2 Produce maximally entangled states of four and more logical qubits.
   - 7.3 Demonstrate the transfer of quantum information between logical qubits.
   - 7.4 Demonstrate simple quantum algorithms (e.g., Deutsch-Josza) with logical qubits.
   - 7.5 Demonstrate fault-tolerant implementation of simple quantum algorithms with logical qubits.

5.0 Considerations

1. Special strengths
    1.1 The use of superconductors ensures an inherently low-dissipation, long-range-phase-coherent technology.
    1.2 The technology is a proven one for fabrication, measurement, and control.
        1.2.1 The technology requires incremental improvements for progress, but not qualitatively new developments [18].
        1.2.2 The fabrication technology enables integration of qubits with custom electronics for fast control and readout [18].
        1.2.3 Established superconducting electronics can be used to engineer the Hamiltonian. The Hamiltonian can also be modified by fabrication and by voltages and currents.
        1.2.4 Relatively strong interactions allow for gating and control, with a very fast speed of operation.
    1.3 A broad diversity of approaches for qubits has already been demonstrated.
    1.4 The preparation of a pure state is easy; it relies only on cooling the qubit to low temperatures.

2. Unknowns, weaknesses
    2.1 Sources of noise need to be identified and the mechanisms of relaxation and dephasing need to be quantified. Are there new mechanisms of decoherence that can only be observed in highly entangled systems?
    2.2 Quantitative comparisons need to be made on the experiments and theory concerning the effect of the electromagnetic environment on one-qubit operations and dephasing and relaxation times.
    2.3 Characterization of the fabrication of qubits and associated circuitry needs to be standardized by developing standards for the quality of junctions; reducing flux, charge, and critical-current noise; and assessing the best material.
    2.4 Inherent nonuniformity of the qubits from fabrication inaccuracies needs to be assessed theoretically and experimentally.
    2.5 Broad diversity of approaches for qubits, control, and measurement possibilities will require an assessment of these types.

3. Goals 2002–2007
    3.1 The physical limitations of single and coupled physical qubits will be understood and controlled.
        3.1.1 Major sources of decoherence in superconducting systems will be identified and quantified.
        3.1.2 The effect of the electromagnetic environment will be controlled.
        3.1.3 Phenomenological theories of measurement and control.

3.2 Three-to-five entangled qubits will be demonstrated and controlled in various types of qubits.

3.2.1 Two-qubit gates and simple algorithms will be demonstrated.

3.2.2 On-chip superconducting electronics will be used for the manipulation of a single qubit for some approaches.

3.3 A plan will be developed for scaling to 10 physical qubits.

3.4 An assessment will be made of the alternative types of qubits and fabrication schemes.

3.4.1 Some narrowing of diversity of superconducting qubits will be done.

3.4.2 Reliable fabrication processes and the associated materials issues will be identified.

4. Goals 2007–2012

4.1 Encode a single-qubit state into a logical qubit formed from several qubits.

4.1.1 Demonstrate ten or more entangled qubits.

4.2 Perform repetitive error correction of a logical qubit.

4.2.1 Develop fast control and readout schemes with superconducting electronics.

4.2.2 Reduce noise due to fluctuations of the charge, flux noise, and critical current.

4.3 Plan to be developed for scaling to 100 or more entangled qubits.

4.4 Assess the best types of superconducting qubits.

5. Necessary achievements

5.1 No clear roadblocks exist at this time.

6. Trophies

6.1 A superconducting qubit which is robust during its operation to fluctuations due to charge, flux, and critical current.

6.2 Experimental confirmation of theory to predict decoherence in superconducting circuits.

6.3 Coupling of two superconducting qubits.

6.4 Fast control and manipulations of a qubit with on-chip superconducting electronics.

6.5 Fabrication process capable of producing qubits with long coherence times and integration of SFQ electronics.

6.6 Theory to assess and to overcome the effects of the inherent fabrication differences in qubits.

6.7 Development of fault-tolerant schemes for superconducting qubits.

6.8 Development of interfaces between disparate quantum technologies (e.g., microwaves and superconducting qubits) for flying qubit.

6.9 Novel uses of superconducting qubits.

7. Connections with other quantum information science technologies
   - 7.1 Improved instrumentation and sensors operating at the quantum limit that use entanglement and squeezing.
   - 7.2 Experimental tests of quantum mechanics on a macroscopic scale.
   - 7.3 Superconducting devices are being used as single photon detectors (SPDs) for quantum key distribution [19].

8. Subsidiary developments
   - 8.1 Improved instrumentation and sensors operating at the quantum limit that use entanglement and squeezing will be developed.
   - 8.2 Experimental tests of quantum mechanics on a macroscopic scale will be possible with some types of superconducting qubits.

9. Role of theory
   - 9.1 Develop a detailed theory of the sources of decoherence.
   - 9.2 Formulate a theory for scaling, including threshold theorems for particular architectures.
   - 9.3 Develop fault-tolerant schemes which use the unique properties of superconductor.
   - 9.4 Design novel architectures to exploit better algorithm implementation.
   - 9.5 Design novel uses of superconducting qubits for quantum-limited instrumentation.
   - 9.6 Make a more generic the connection between classical dissipation and quantum decoherence.
   - 9.7 Develop methods of determining degree of entanglement and benchmark the fidelity of operations of multiqubit systems
   - 9.8 Optimize error correction for realistic noise sources.
   - 9.9 Develop of interfaces between disparate quantum technologies (e.g., microwaves and superconducting qubits.

6.0 Timeline

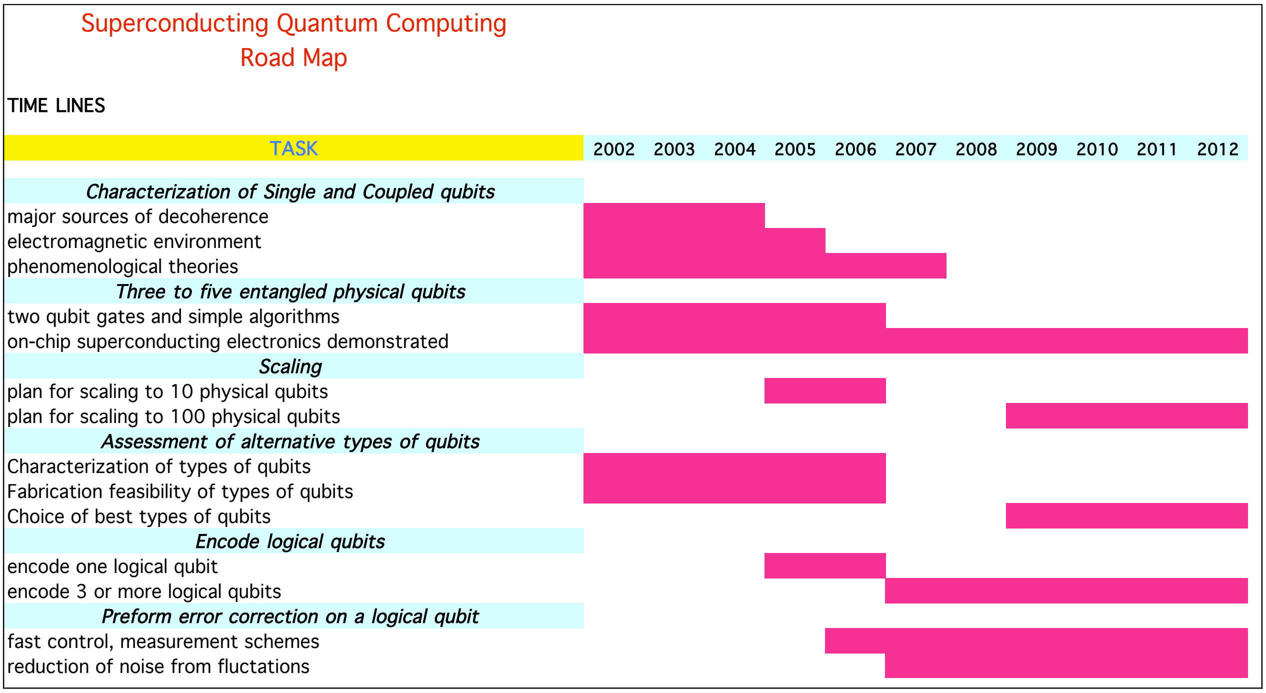

Figure 6-1. Superconducting QC developmental timeline.

7.0 Glossary

8.0 References

Note: The following references mostly detail the experimental progress, and are only a partial list of results. Much of the theory and earlier work is reviewed in Reference 1.

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Probable reference (consistent with words in the citing text):

Title:Decoherence of flux qubits coupled to electronic circuits Author:Wilhelm, FK ; Storez, MJ ; van der Wal, CH ; Harmans, CJPM ; Mooij, JE Institution:Univ Munich, Sekt Phys, D-80333 Munich, Germany Journal:ADVANCES IN SOLID STATE PHYSICS; 2003; v.43, p.763-778 Conference:Spring Meeting of the Argeitskreis-Festorperphysik of the Deutsche-Physikalische-Gesellschaft; March 24-28, 2003; DRESDEN, GERMANY

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