Current Challenges for Quantum Computing

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Back in 1959…

…When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc.

*From “There's Plenty of Room at the Bottom”, Lecture by Richard Feynman at APS meeting in 1959.*
Fast quantum computation

P. Shor, AT&T, 1994

Classical factoring problem required 8 months on hundreds of computers

Shor’s algorithm gives an exponential speedup for prime factorization compared with any known algorithm on an ordinary computer!

Factor $k$-digit number: time

\[ \approx e^{\sqrt{k}} \]

Factors

3490529510847650949
1478496199038981334
1776463849338784399
0820577

3276913299326670954
9961988190834461413
177642979929425397
98288533

Same Input and Output, but Quantum processing of intermediate data gives

Factor $k$-digit number: time

\[ \approx k^2 \]
Outline

- The nature of qubits/quantum algorithms
- Materials and devices for a quantum computer
  - (Solid state perspective)
- Fault tolerance, and the noise threshold theorem
- Strategies for 2D layouts for qubits
- Measurement, Isolation, Amplification
- The full system view
Qubit

Definite state “0”

Definite state “1”

Bloch Sphere

Superposition states (“halfway” shown)

- sometimes has a clear classical meaning, usually not
- must be isolated from environment to exist
- can couple to other qubits, then **entangled** states are formed, e.g., $\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$
A possible qubit:
Single-electron semiconductor quantum dots

Harvard, c. 2004
Another very promising family of qubits: superconducting circuits

From Quantum Optics and Quantum Information Processing with Superconducting Circuits, A. Blais, 2011-used with permission.

Nanoscale tunnel junction required – old technology

\[ V(t) = V_0 \cos(\omega_0 t) \]

\[ I = I_0 \sin(2\pi \Phi / \Phi_0) \]

\[ L_J(\Phi) = \left( \frac{\partial I}{\partial \Phi} \right)^{-1} \]

\[ = \frac{\Phi_0}{2\pi I_0 \cos(2\pi \Phi / \Phi_0)} \]
The quantum gold rush

The science is immature and a multi-purpose quantum computer doesn’t yet exist. But that isn’t stopping investors pouring cash into quantum start-ups.

By Elizabeth Hackett

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Google

IBM
Quantum computers are here?

(IBM’s 50-qubit superconducting quantum computer)

Certainly an amazing scientific instrument: An apparatus for controlled scattering of quantized radiation – think particle detectors

Note growing size to accommodate huge cable bundles
Situation with scale-up. 16-qubit IBM cloud quantum computer

Metalized structure on Si chip

(all resemblance to normal chips ends there.)

Qubit possibilities are superconducting/SQUID type
single electron type
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16 qubits (highlighted white)
active part is nanometer scale

Massive additional structures
are resonant couplers,
sections of coplanar waveguides
Another way of saying what parts are on the IBM chip:

46 resonators
All at microwave frequencies
All very high quality factor \((10^7)\)
30 "normal" CPW resonators
16 qubit resonators
   --- 1 photon enters, no more
   --- 0/1 is qubit

Kept almost perfectly still
\(T=0.02\) K
Example of problematic situation: 16-qubit IBM chip

Qubits indicated are not supposed to have any direct entangling interaction

Nevertheless there is one, at the 1 MHz level

Not very big, but $10^4$ linewidths!
Black-box modeling methodology

Black box modeling formulas:


- Introduces new formulas for qubit J couplings, drive crosstalk, and other quantities, in terms of multiport impedance
- The 7-port “gray-box”, or the 10-port IBM device on the right can be accurately simulated with HFSS, given the full impedance matrix
- E.g., J-coupling formula:

\[ J_{ij} = -\frac{1}{4} \sqrt{\frac{\omega_i\omega_j}{L_iL_j}} \text{Im} \left[ \frac{Z_{ij}(\omega_i)}{\omega_i} + \frac{Z_{ij}(\omega_j)}{\omega_j} \right] \]

\[ H = J_{ij}(X_iX_j + Y_iY_j) + \ldots \]
Very good theory-experiment correspondence for J couplings

An impression of the meshing needed in the microwave simulation
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See JVH_IEDM_tutorial2014.pdf
Prospects: a Moore’s law for coherence
For superconducting qubits

$t_{\text{gate}}/T_2 \approx 5 \times 10^{-3}$

= noise threshold
of 2D surface code scheme

Coherence time of superconducting qubits
anticipated gate time
approximately 30 nsec

$T_2 > 75 \mu\text{sec}$
reported, L. DiCarlo, Oct. 2011

$T_2 > 95 \mu\text{sec}$
reported, Rigetti et al., Mar. 2012

$T_2 \approx 150 \mu\text{sec}$ rep.
Schoelkopf et al., June 2012

The problem:
Effective time to failure must be $10^{14}$ longer! Massive error correction needed!
Present-day experiments: multiqubit layout to achieve connectivity for quantum error correction

Logical-qubit operations in an error-detecting surface code

Surface code fabric – one version of topological quantum error correction

- Physical qubits encoding the quantum data
- Physical qubits functioning as ancillas, which must be repeatedly measured
Topological 2D Surface Code

• Theoretical results* show that effective fault tolerant quantum computing can be done with local interactions in 2D

![Diagram of a 2D surface code](image)

c. 1% noise threshold


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Regular square lattice of coupled qubits make an effective architecture for fault tolerance

- Qubits (green) coupled via high-Q superconducting resonators (gray)
- “skew-square” layout of qubits and resonators is one way to achieve abstract square
- Every qubit has a number of controller and sensor lines to be connected to the outside world (gold pads)

“In a machine such as this there are very many other problems due to imperfections. . . . At least some of these problems can be remedied in the usual way by techniques such as error correcting codes . . . But until we find a specific implementation for this computer, I do not know how to proceed to analyze these effects.”

R.P. Feynman
“Quantum Mechanical Computers”
Optics News, February 1985

DP. DiVincenzo,
“Fault tolerant architectures for superconducting qubits,”
Present-day experiments: multiqubit layout to achieve connectivity for quantum error correction
State of the art (2015):
Fully controlled 9-qubit device (UCSB/Google)

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Real instrumentation for qubit protection, manipulation, and measurement
State of the art (2015):
Fully controlled 9-qubit device (UCSB/Google)

UCSB/Google

Classical control: 23 control wires for the 9 qubits!
Waveforms of classical signals going to the dilution refrigerator

10 kW power consumption

FIG. S27. Waveform data for eight cycles of the nine qubit repetition code.
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Similar architecture concept, single-electron qubits (can also achieve alternative “logntudinal” coupling)

comment about the control lines:
The ugly part of the architecture – meter-long cable runs to control-room instrumentation

Number of cables ~ 2x the number of qubits

Millions of qubits ???
Vision: Scalable architecture – needs cold analog & digital electronics

Ethernet – „Give your quantum computer an IP address“

Signal generators, amplifiers, isolators, ADCs, DACs

Operating temperature: 4K

Quantum chip: T=0.02K
Outline -- Wrapup

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Useful Literature:


• [www.qurope.eu](http://www.qurope.eu) Quantum Information Processing and Communication in Europe (2016 outlook and beyond)
Vision: scalable architecture
(H. Bluhm)
What will the first Quantum Computers Look Like – vs. a Conventional System?

Classical System

Inputs

Clock P < 1ns

Outputs

QC System

Inputs

Clock P > 10 ns

Inputs

Outputs

Combinational Logic

Memory

Measure

Transducer

Measure

Transducer

Measure

Transducer

Combinational Logic

Memory

Measure

Transducer

Measure

Transducer