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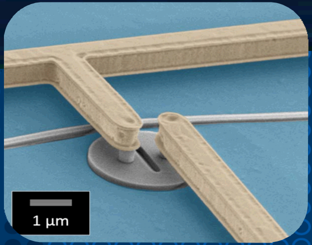

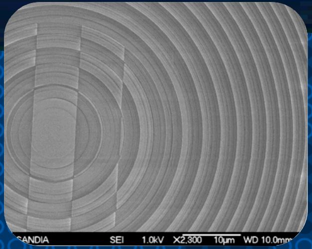

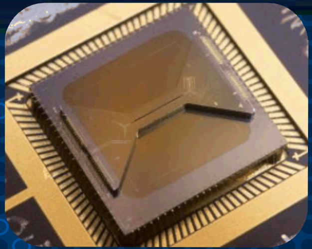

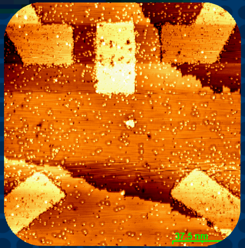

Quantum Computing:

Engineering Challenges and Underlying Technologies

Andrew J. Landahl
Center for Computing Research
Sandia National Laboratories
15 June 2017

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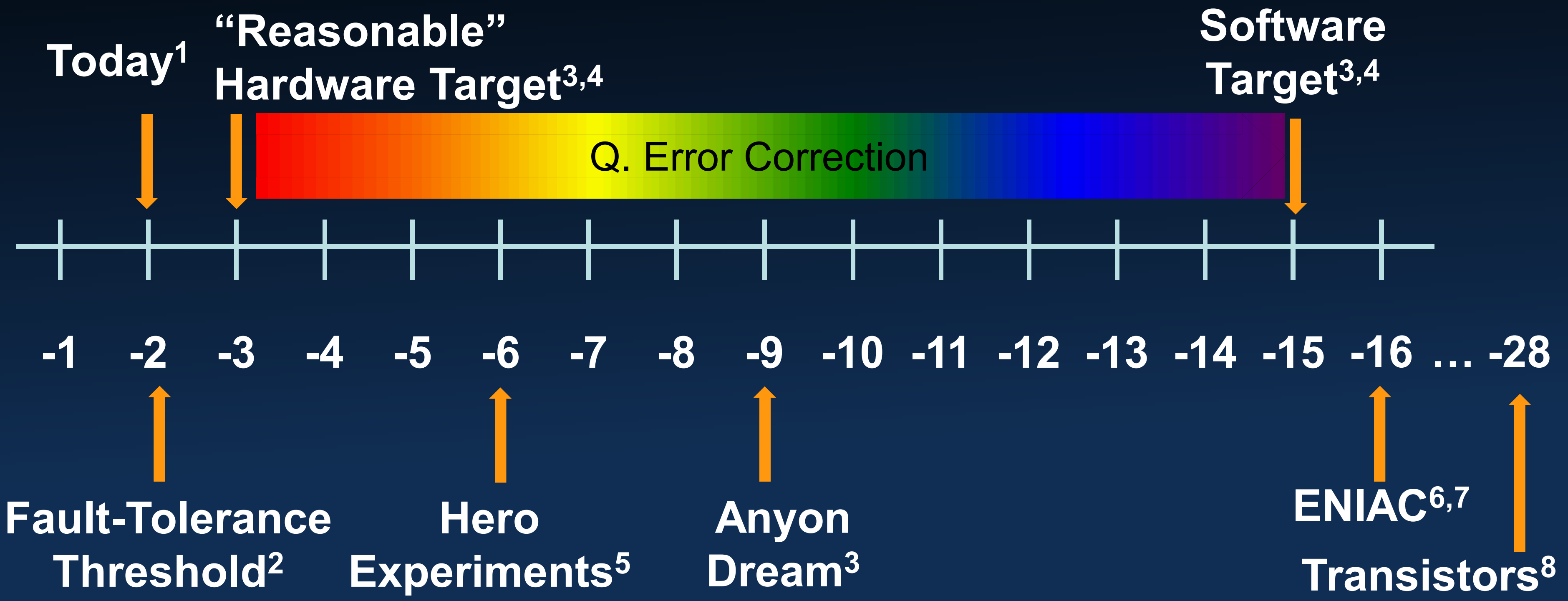
#1 Challenge: Errors

Chart: Quop error probabilities ($\log_{10}$)



Mantra

The logical qubit is the analogue of the electronic bit

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Outline

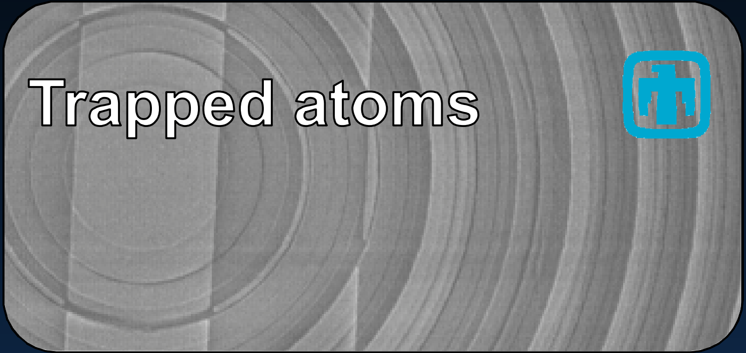
The first 10X: Hardware

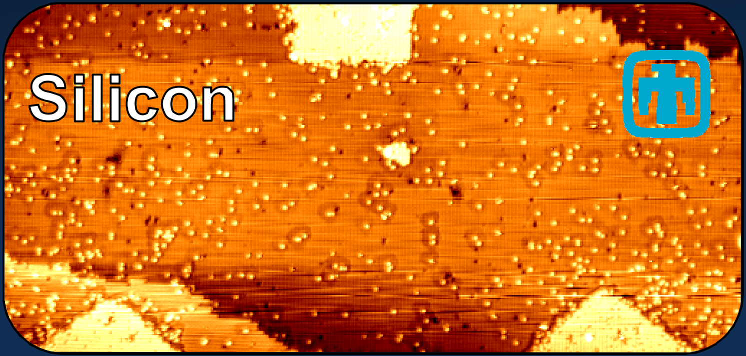
The next 10^{12}X: Architecture

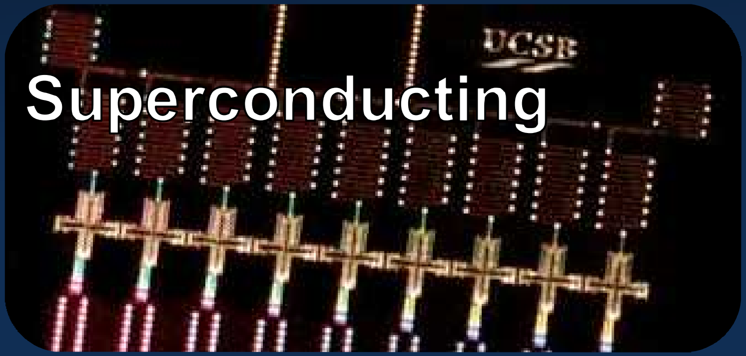
The first 10X:
Hardware

Quantum Chips

Each has its strengths & weaknesses







Images: Sandia, UCSB (Julian Kelly)

Environmental Controls

Cryogenics

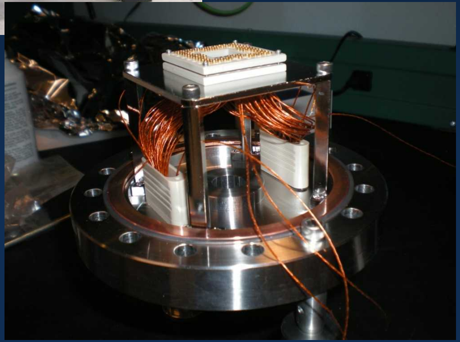
- Low-power, hi-speed signal feed-thrus
  - Analog ***and*** digital
- Low-power cryogenic amplifiers
- Increased cooling power (<< 4K)

Vacuum

- UHV (10^{-11} torr) for atoms & ion qubits
- Vacuum feed-thrus (electrical and optical)
- Vacuum-compatible materials

Electromagnetic

- Helmholtz coils
- Faraday cages
- Local low-frequency EM-field compensation
- High-powered magnets



Images: Sandia

Devices & Signaling

Materials

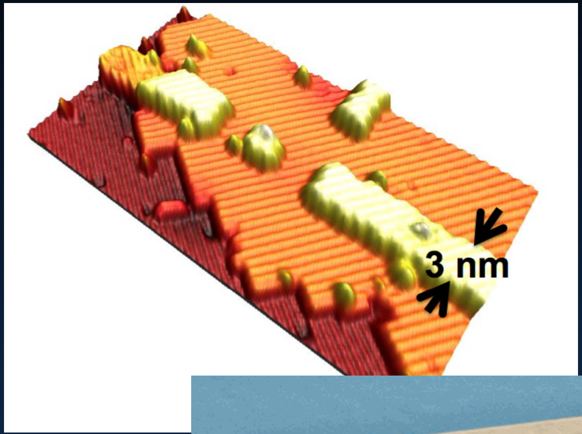
- “Quantum-grade” silicon, diamond
- Integrated nanostructures
- Engineered quantum behaviors

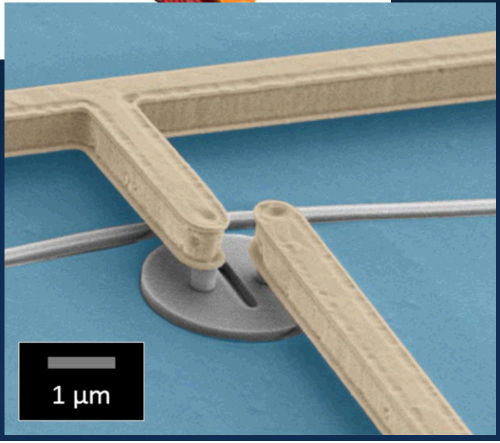
Electronics

- Fast & precise low-power DACs
- Superconducting control electronics
- Error syndrome decoders

Interconnects

- Unusually high-quality required:
  - Low power, low-loss, low-crosstalk
  - Wide-bandwidth, long-distance
  - Phase-locked, polarization-maintaining
- Holy Grail: Coherent quantum transducers





Images: Sandia[13]

The next 10^{12}X:

Architecture

Architecture

Design in the face of constraints[9,10]

Environment

- Cooling power limits
- Vacuum limits
- EM control limits

Devices & Signals

- Yield limits
- Parallelism limits
- Latency limits
- I/O limits
- Routing limits

System

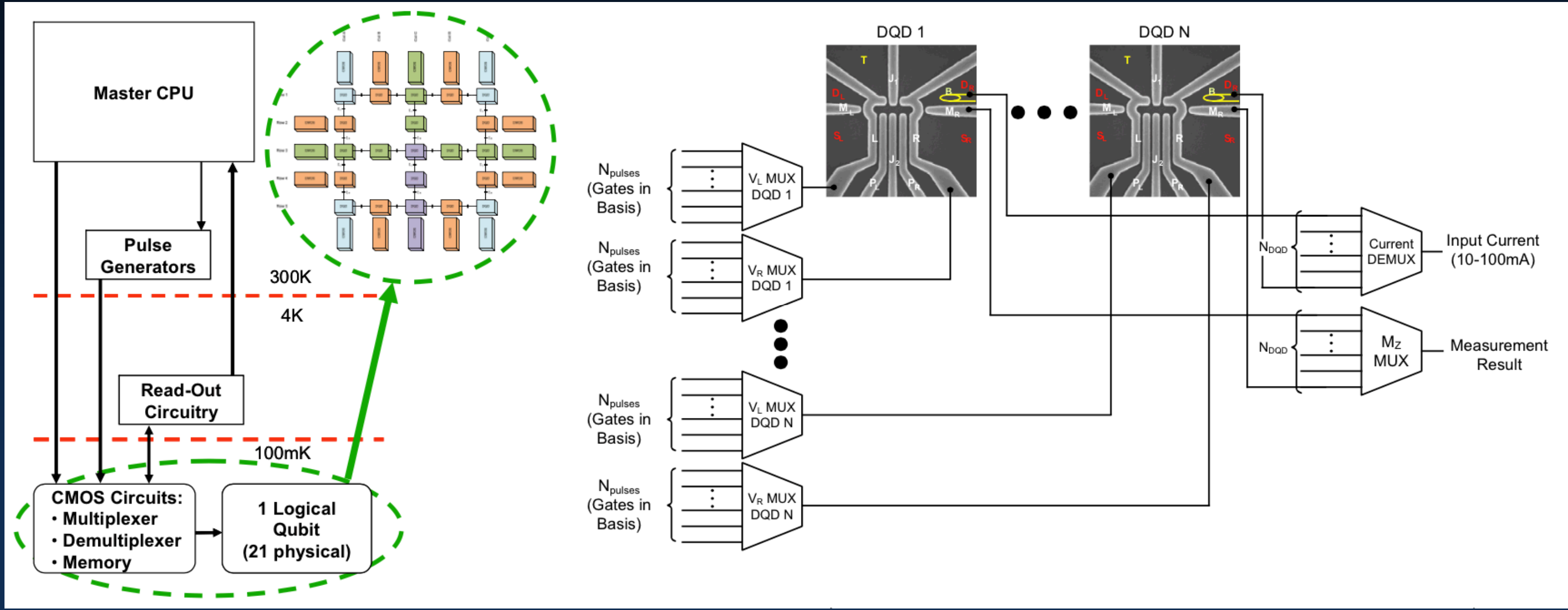
- Power limits
- Floor space limits
- Dollar limits

Images: Wikipedia:
Flatiron building (Edifici Fuller), Igloo (Maurizio Ceol), Sod House (Christian Bickel)

Case Study: Bacon-Shor

Electronics constraints radically change conclusions[9,10,11]

W/o constraints[12]**:** $p_{th} = 5.0 \times 10^{-4}$ **W/constraints**[10]**:** $p_{th} = 2.0 \times 10^{-5}$



Images: Sandia[10]

Fault-Tolerance Cost

Trading quality for quantity

Factoring a 2,000-bit number[4]:

- 10^{12} quops deep, 4,000 qubits wide (error-free)
- Errors demand logical (encoded) qubits and logical (encoded) "magic states" to facilitate fault tolerance
  - 10^{-3} error: 1.02 Gqb (physical).
  - 10^{-4} error: 130 Mqb (physical).

Fault-Tolerance Cost

Trading quality for quantity

Quantitatively accurate simulation of FeMoCo[3]:

- 10^{12} quops deep, 135 qubits wide (error-free)
- Errors demand logical (encoded) qubits and logical (encoded) “magic states” to facilitate fault tolerance
  - 10^{-3} error: **5.1 Gqb (physical).**
  - 10^{-6} error: **30 Mqb (physical).**

Architecture Challenges

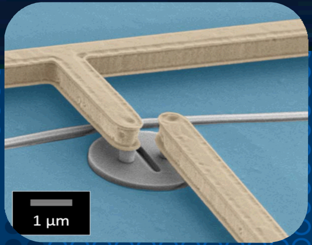
- Codes well-matched to HW constraints
- Codes well-matched to SW applications
- More efficient methods for error-corrected universal QC
- Data from testbed machines on errors in QEC
  - QEC is the killer app for a testbed machine

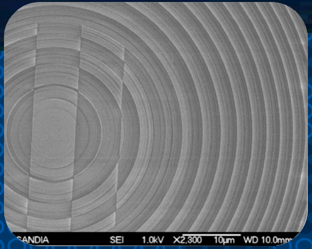
References

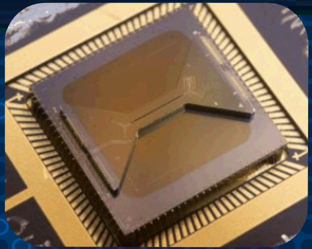
1 Linke *et al.*, Proc. Natl. Acad. Sci. **114**, 3305 (2017).
2 Raussendorf *et al.*, New J. Phys. **9**, 199 (2007).
3 Reiher *et al.*, arXiv:1605.03590 (2016).
4 Fowler *et al.*, Phys. Rev. A **86**, 032324 (2012).
5 Harty *et al.*, Phys. Rev. Lett. **113**, 220501 (2014).
6 Bose, IEEE Micro **26**, 5 (2006).
7 wikipedia.org/wiki/ENIAC (2017).
8 research.ibm.com/acas/projects/01prem.pdf (2017)
9 Levy *et al.*, New J. Phys. **13**, 083201 (2011).
10 Levy *et al.*, arXiv:0904.0003 (2009).
11 Van Meter & Oskin, ACM J. Emerging Tech. in Comp. Sys. **2**, 31 (2006).
12 Cross *et al.*, Quant. Inf. Comp. **9**, 0541 (2009).
13 Gehl *et al.*, Optica **4**, 374 (2017).

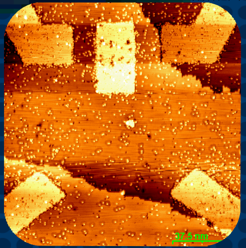
Technical Assessment of the Feasibility and Implications of Quantum Computing

National Academies of Sciences, Engineering, and Medicine









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