Challenges in Building Quantum Computers

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Computing Sciences Summer Student Program Talk

Berkeley, CA

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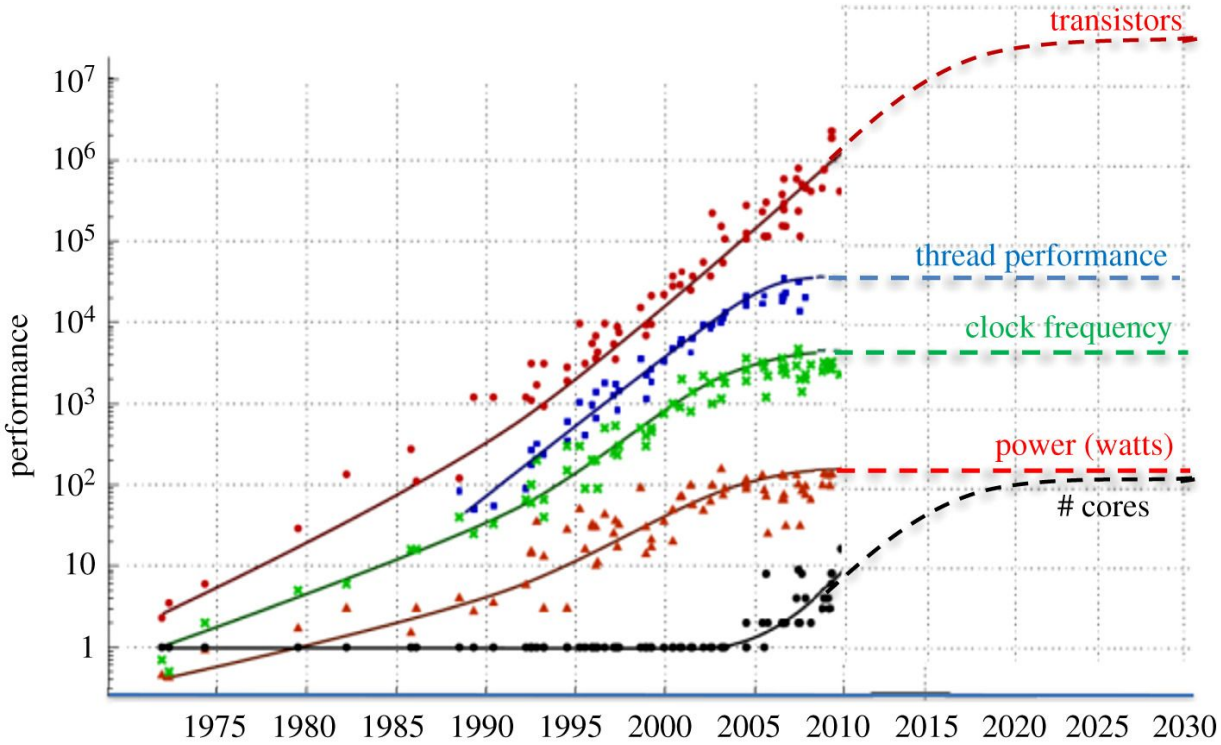
Quantum Computer

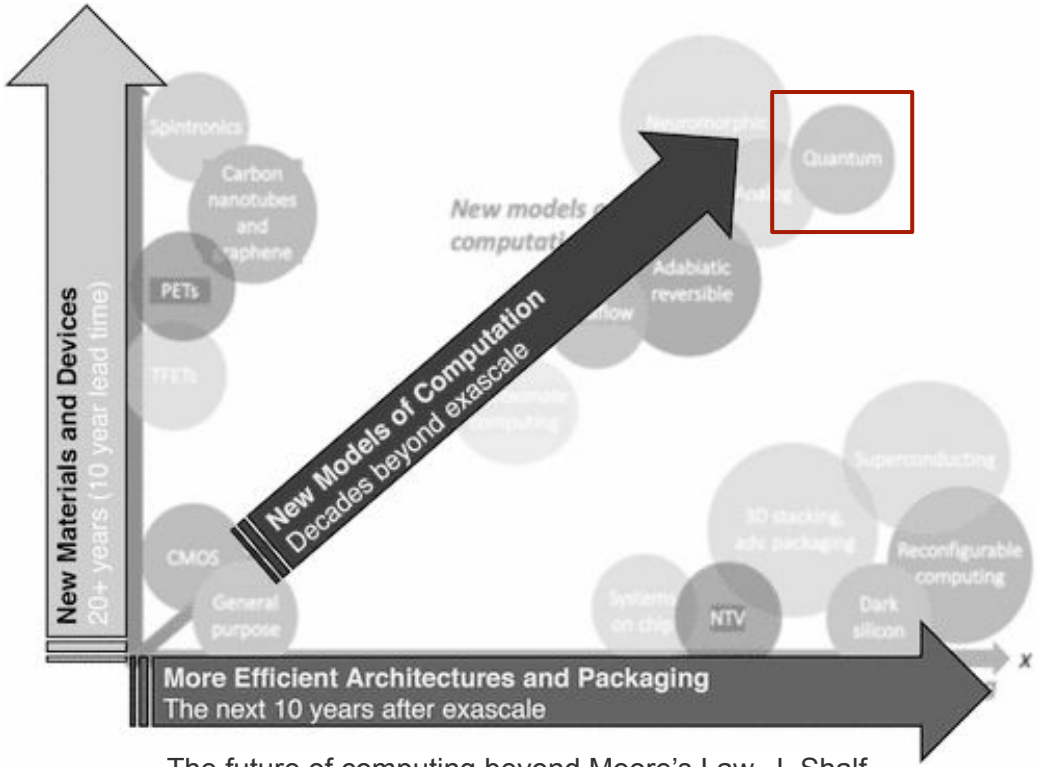
Why?

As the Moore's Law ending...



Kunle Olukotun, Lance Hammond, Herb Sutter, Mark Horowitz and extended by John Shalf.

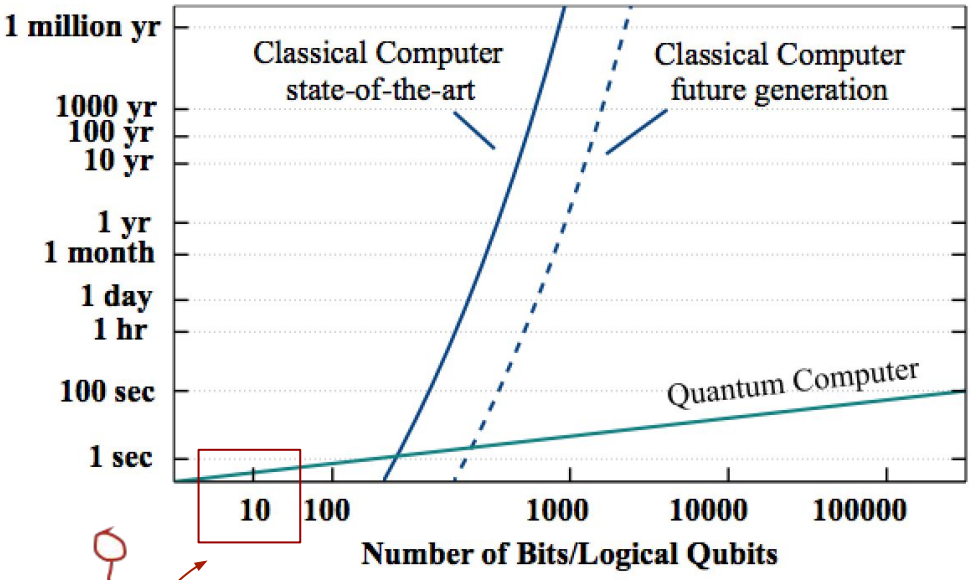
Continued Performance Improvements



The future of computing beyond Moore's Law, J. Shalf

As the Moore's Law ending...

Number factorization problem



We are here

Quantum Computer

Myth or Reality?

Myth or Reality?

Google

quantum computer

People also ask

Do quantum computers exist now?

How powerful is a quantum computer?

Who has a quantum computer?

How much does a quantum computer cost?

Timeline

1994
Peter Shor invents the (in)famous **Shor's algorithm**, sparking a tremendous increase of interest in Quantum Computing

2018
Quantum supremacy (the potential ability of Quantum Computing devices to solve problems that classical computers practically cannot) is reached

2019
Organisations are preparing for the quantum revolution by **education** and raising awareness

2025
Financial services begin to leverage Quantum Computing

2035
Great amount of **business** cases in production environments

2038 - ...
What's next...

1998
The first working **2-qubit Quantum Computer** demonstrated

2019
IBM launches first 20-qubit **commercial quantum computer** named Q System One

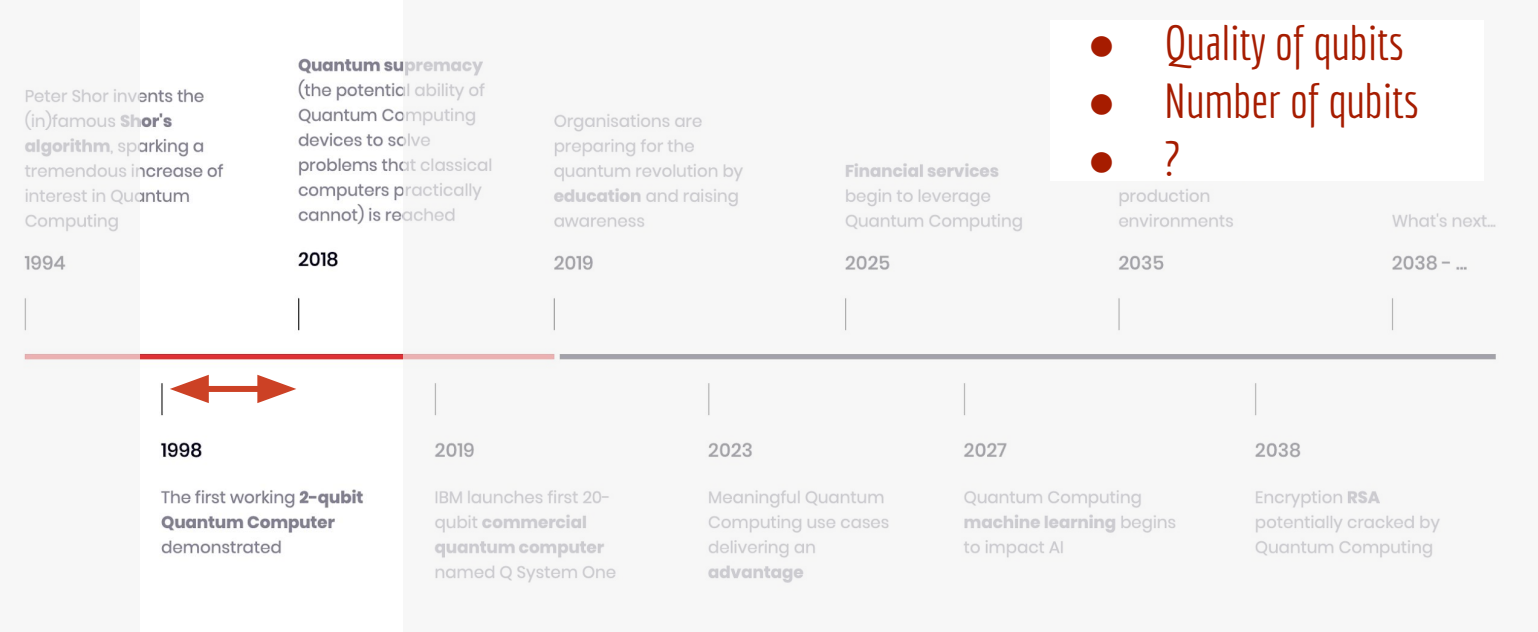
2023
Meaningful Quantum Computing use cases delivering an **advantage**

2027
Quantum Computing **machine learning** begins to impact AI

2038
Encryption **RSA** potentially cracked by Quantum Computing

QNTM: Entering the era of Quantum Computing
www.qntm.be

Timeline



- Quality of qubits
- Number of qubits
- ?

QNTM: Entering the era of Quantum Computing
www.qntm.be

Challenges

Quality

Quality of Qubits

Extremely sensitive to noise

- from outside environment
- from neighboring qubits
- from ``nowhere''

Research directions

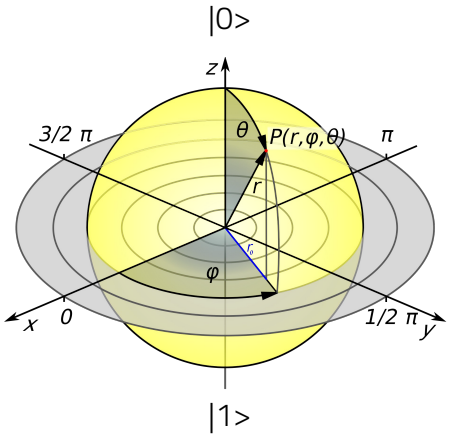
- noise modeling
- noise mitigation
- qubit isolation

remove

- error correction

ignore

Bloch sphere



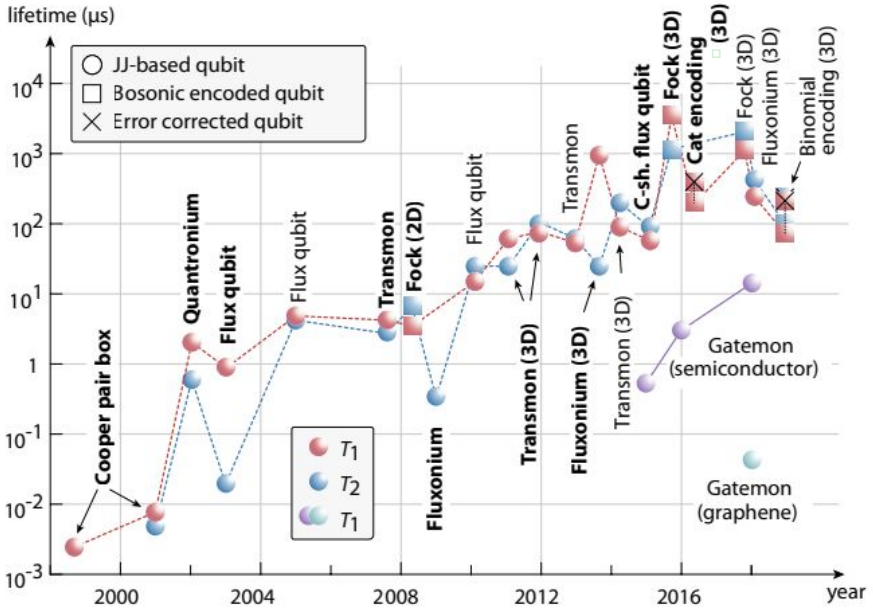
Quality of Qubits

Has limited *lifetime*

- depends on technology

Research directions

- material science/technology

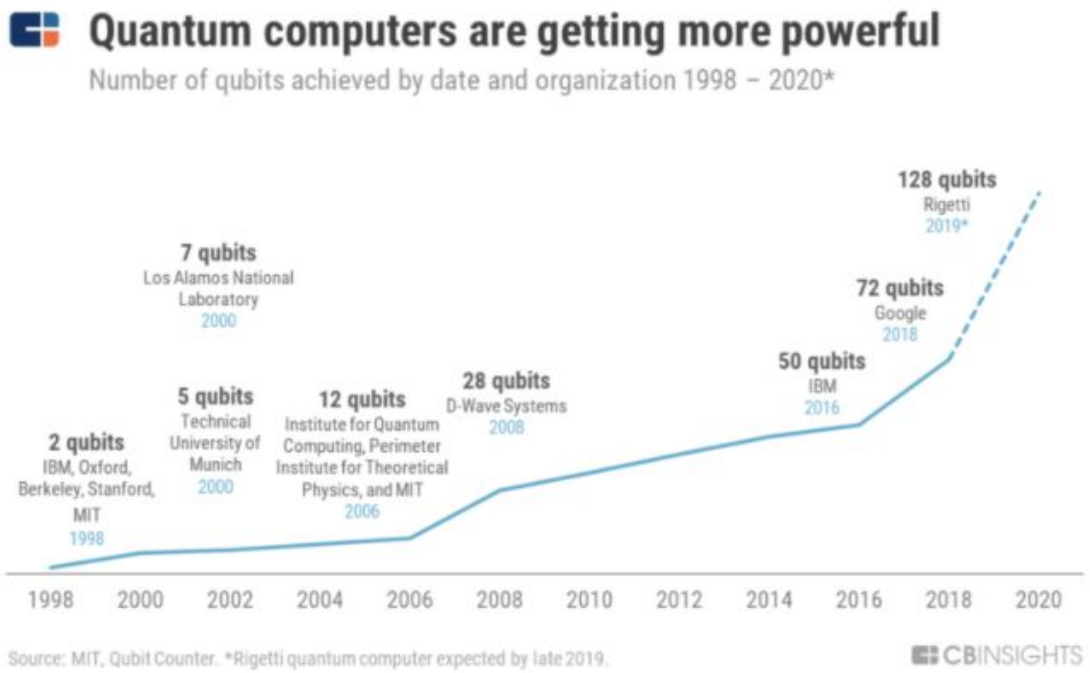


Superconducting Qubits: Current State of Play, Kjaergaard et al.

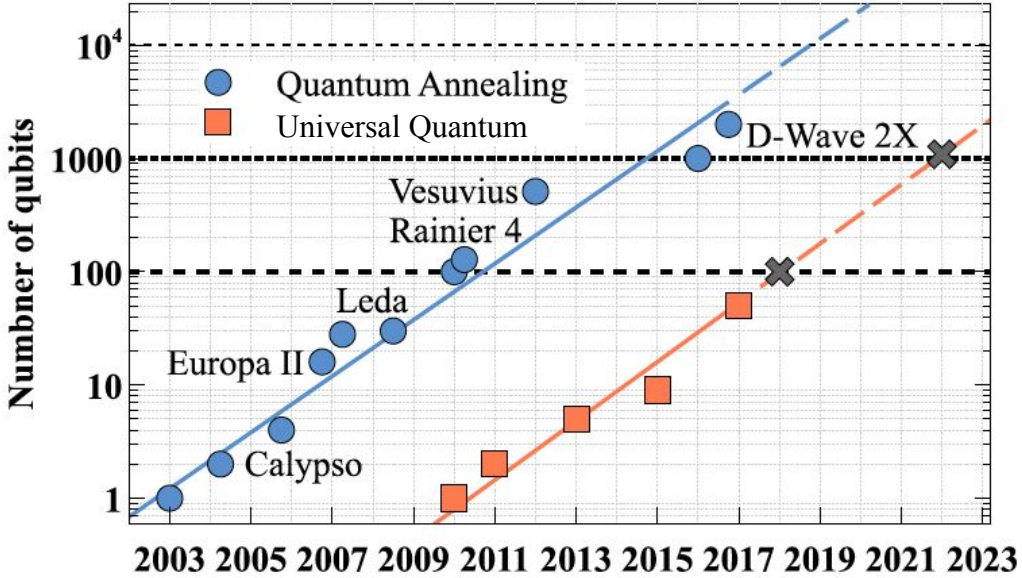
Challenges

Number of Qubits

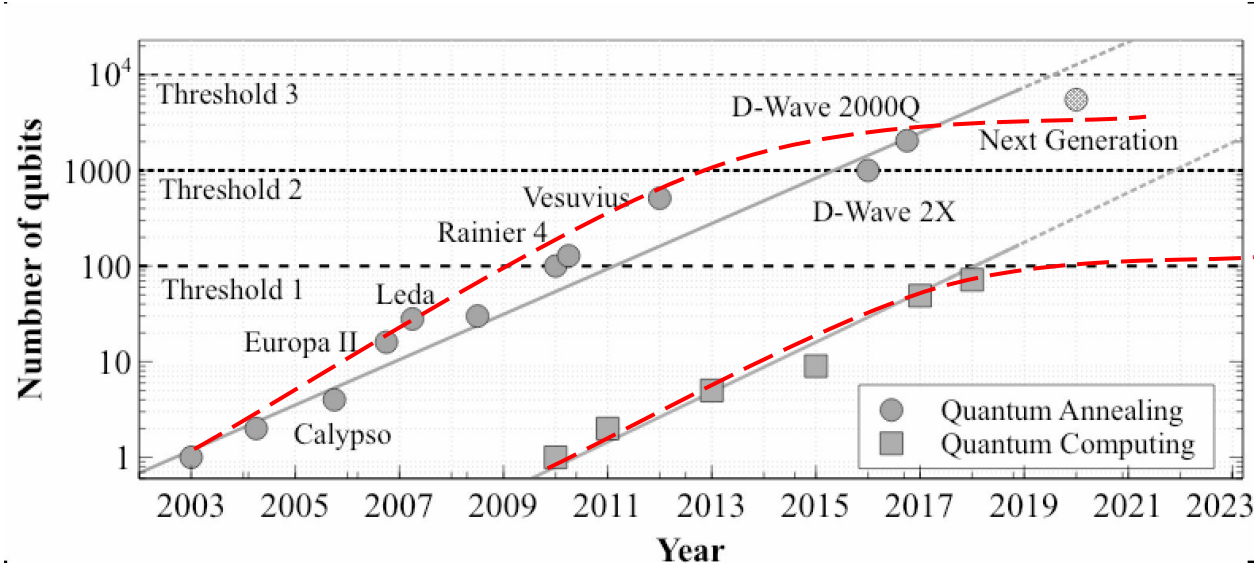
Number of Qubits



Number of Qubits



Number of Qubits

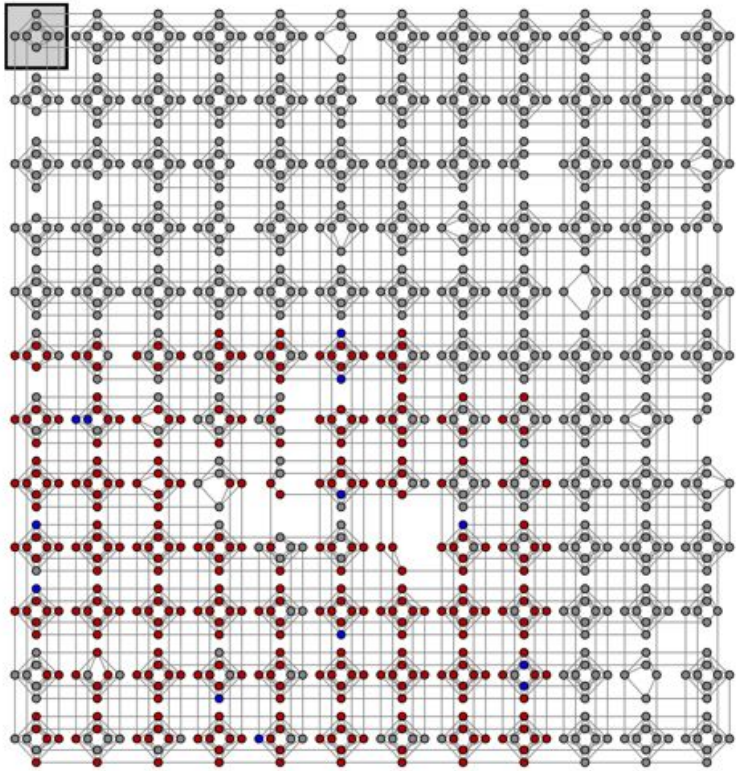


Number of Qubits

D-Wave Quantum Annealers

- Chimera topology (not all-to-all connectivity)
- Number of logical qubits << physical qubits

	Logical		Physical		Total	
	Qubits	Couplers	Qubits	Couplers	Q: 1095	C: 6122
Problem 1	44	314	128	398	12.00%	6.50%
Problem 2	176	5192	1768	6672	162.00%	109.00%



Challenges

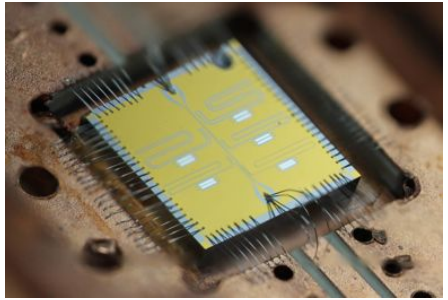
Anything else?

Quantum ~~Computer~~ Accelerator

Inaccuracy of terminology

- Quantum computer ≠ Quantum Processing Unit (QPU)

≠



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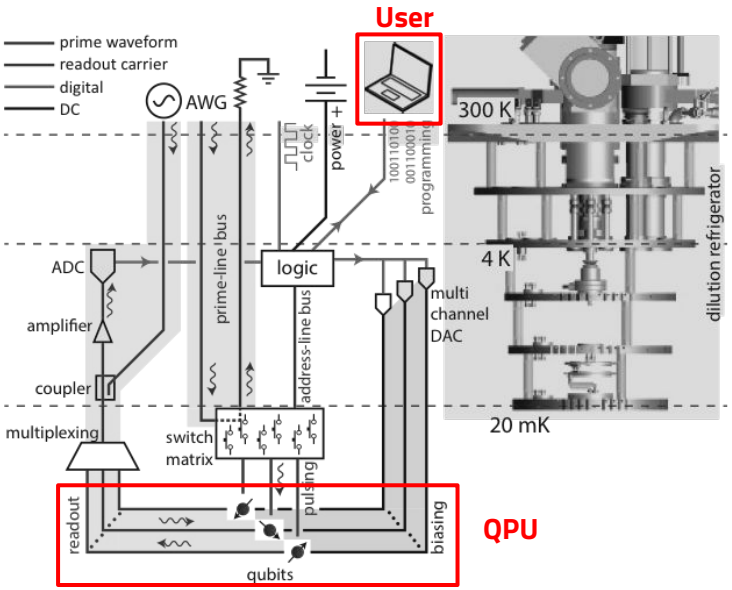
Quantum ~~Computer~~ Accelerator

Inaccuracy of terminology

- Quantum computer ≠ Quantum Processing Unit (QPU)
- Quantum computer = QPU + Control Hardware



Cryogenic Control Architecture for Large-Scale Quantum Computing, J. M. Hornibrook et al., Phys. Rev. Applied 3, 024010, (2015)

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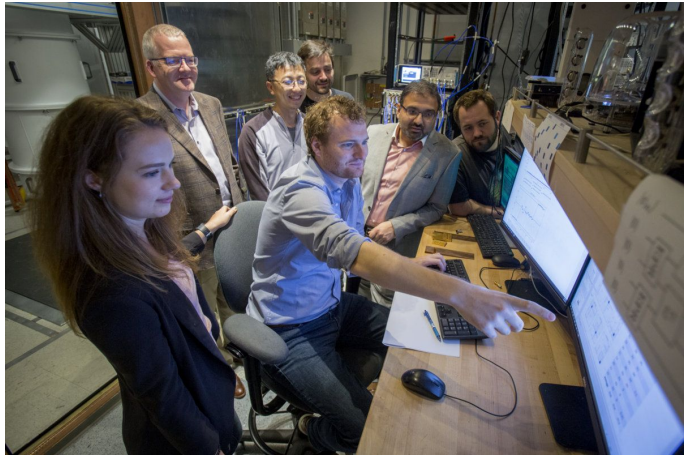
Advanced Quantum Testbed (AQT)

- DOE funded cross-disciplinary project
  - Open collaboration
  - $30 million over 5 years
    - quantum physicists (QNL, MIT LL)
    - material scientists (MF)
    - **computer scientists (CRD)**
    - engineers (ATAP)
    - industry partners



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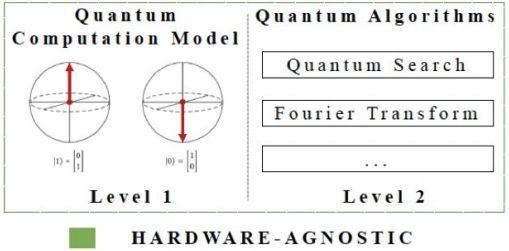
Challenges

Control System

Main concepts

Theory



Main concepts

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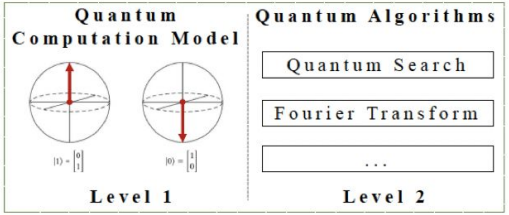
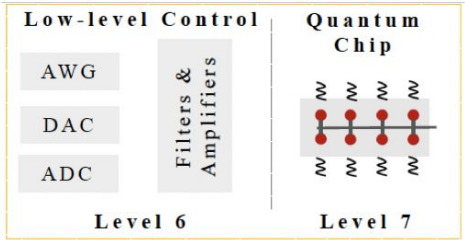


HARDWARE-AGNOSTIC

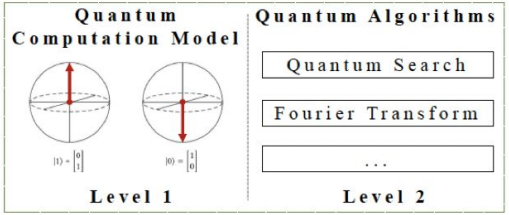
Practice



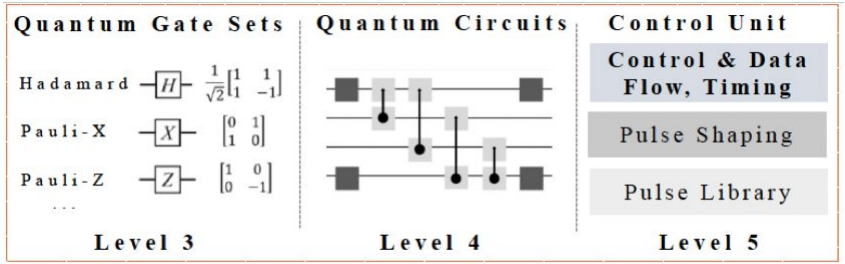
SOFTWARE-AGNOSTIC

Main concepts

Theory

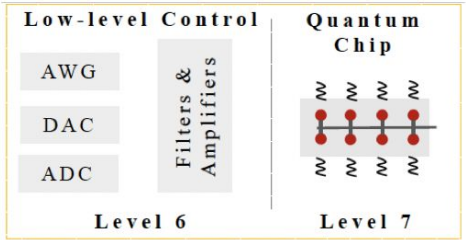


HARDWARE-AGNOSTIC



HARDWARE- & SOFTWARE-AWARE

Practice

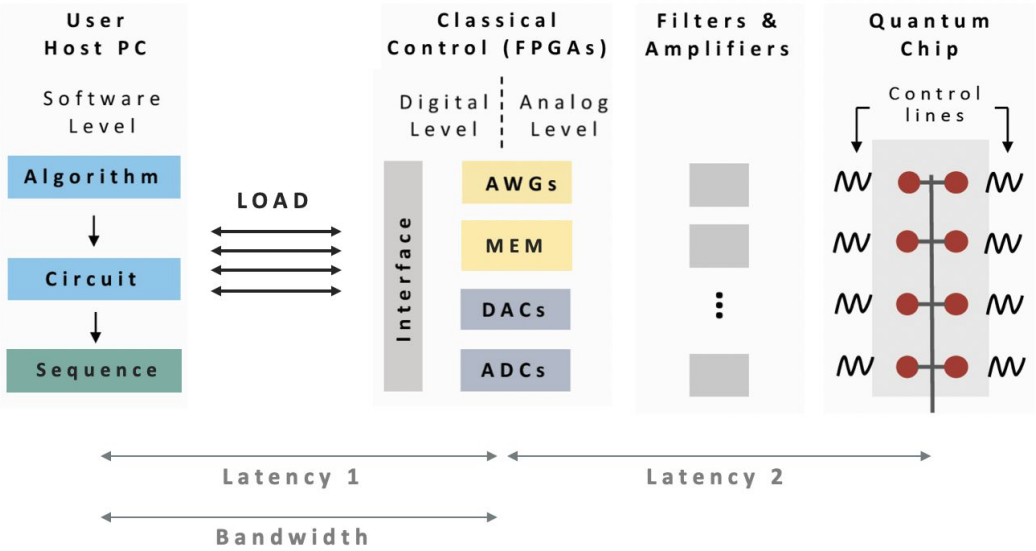


SOFTWARE-AGNOSTIC

Control System Architecture

Locality & Functionality

Traditional User-to-QPU path



Software Control

- Everything in one place ✅
- Easier to implement and modify ✅
- NISQ experiments ✅

- Long latency ❌
- Limited bandwidth ❌
- Limited flexibility (bit granularity) ❌
- Poor scalability ❌

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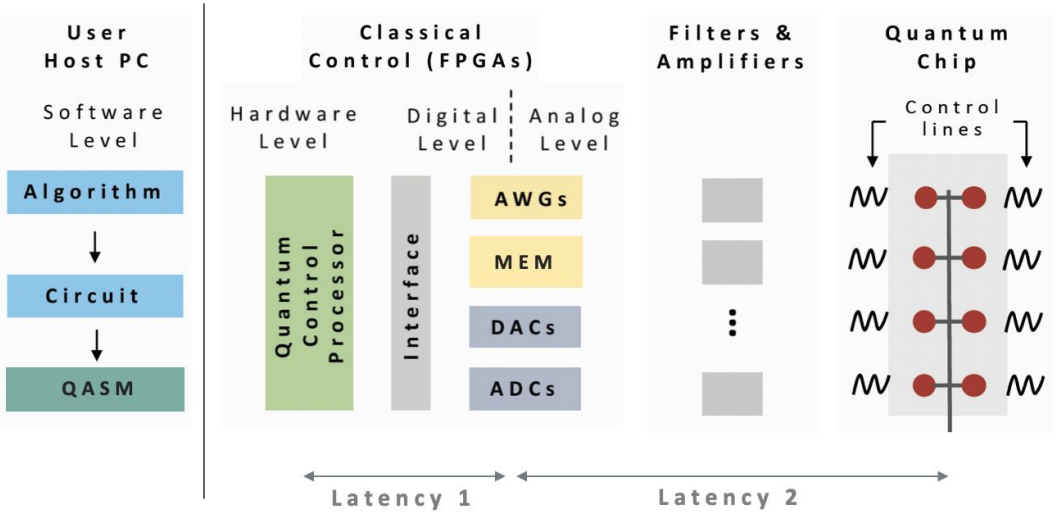
Bringing intelligence to the edge



Hardware Control

- Reduced latency ✅
- Fast feedback ✅
- Extended functionality in-place ✅
- Potential scalability ✅
- Separation of concepts ✅
- Beyond-NISQ ✅

- Requires specialized solution ❌
- Harder to implement and modify ❌

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Quantum Control Processor

What is a measure of success?

Quantum Control Processor success

FLOPS? Energy? Execution time? Power consumption?

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Quantum Control Processor success

~~FLOPS? Energy? Execution time? Power consumption?~~

Task #1: Provide control pulses <u>on time</u>

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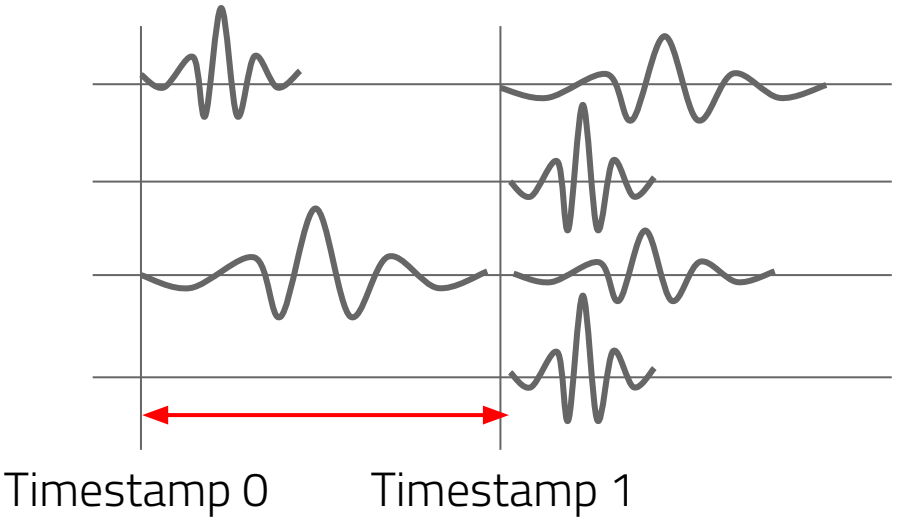
Quantum Control Processor success

~~FLOPS? Energy? Execution time? Power consumption?~~

Task #1: Provide control pulses <u>on time</u>



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Quantum Control Processor success

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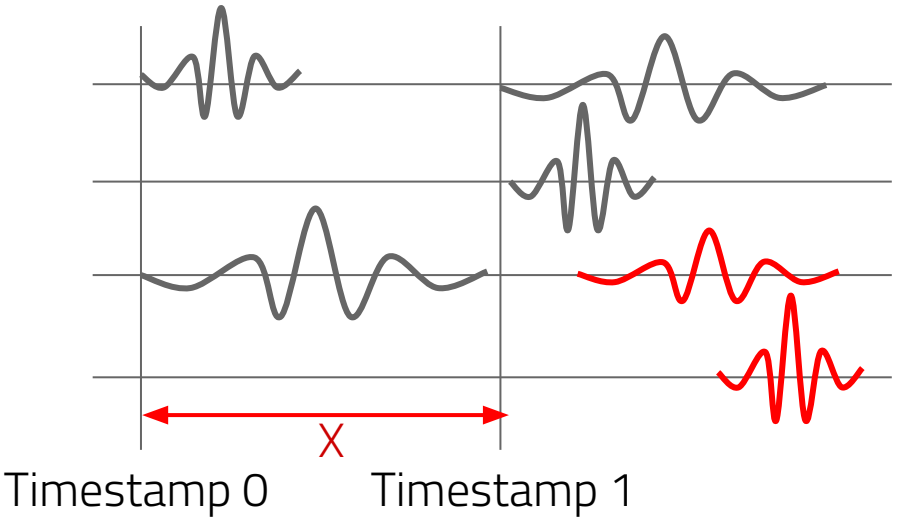

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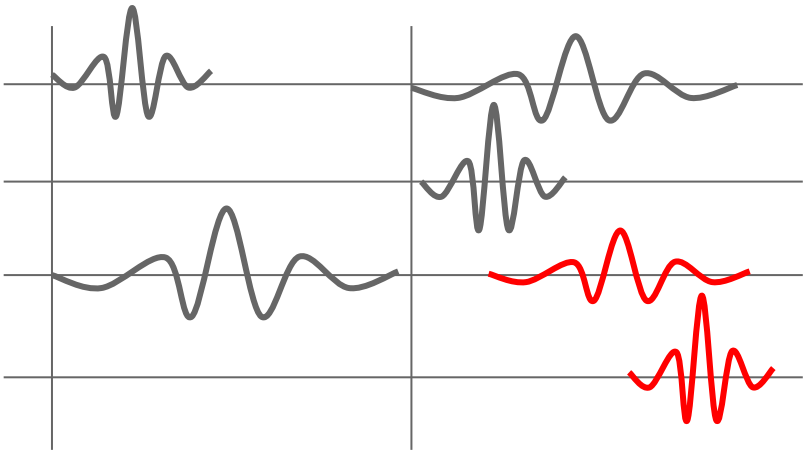
Quantum Control Processor success

~~FLOPS? Energy? Execution time? Power consumption?~~

Task #1: Provide control pulses <u>on time</u>



Sub-circuit complexity

lower

higher

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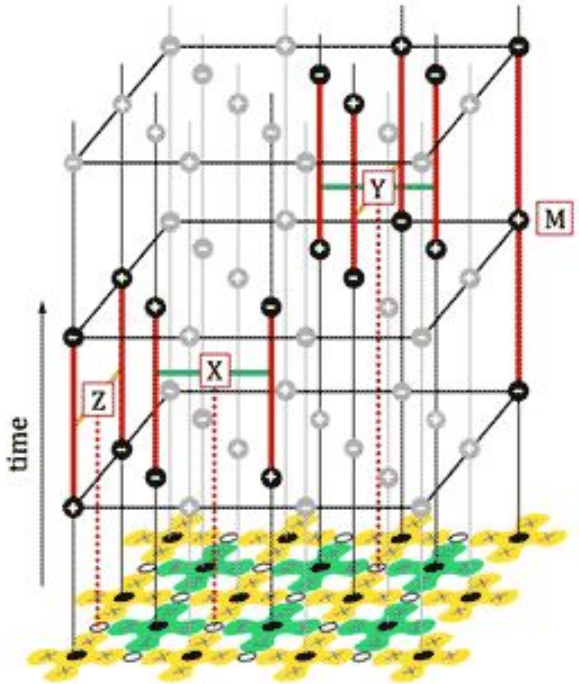
Quantum Control Processor success

- fast -feedback loop & bit manipulation



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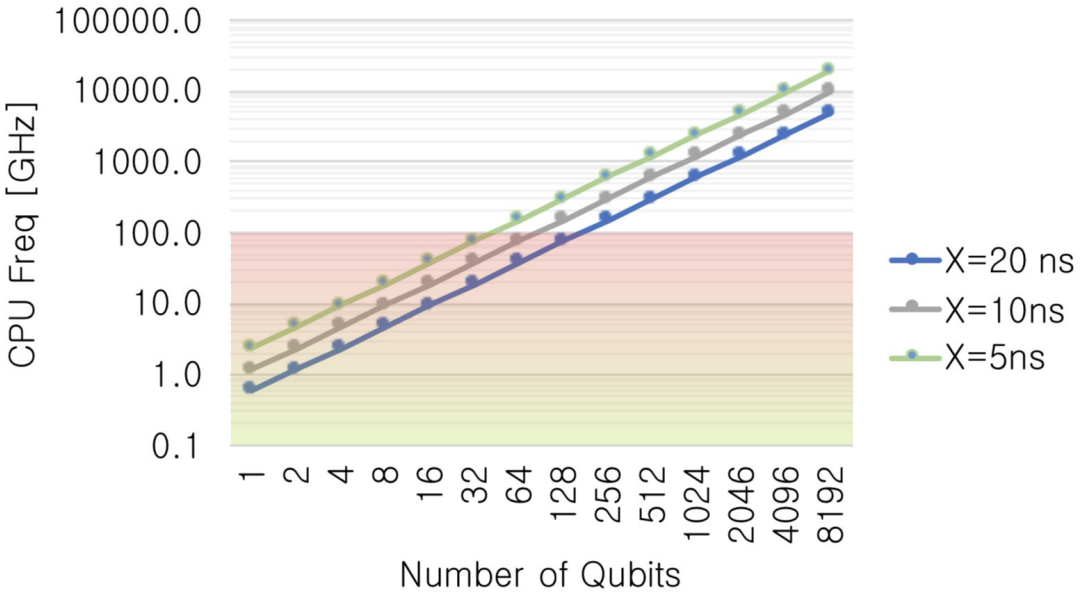
The University of Melbourne Topological Quantum Error Correction (TopQEC) group

Control processor speed estimates

RISC assembly MM control interpretation per one cycle

- 4 instructions/gate → 12 operations/gate
- N qubits → 12*N operations/gate
- gate delay → 20ns, 10ns, 5ns



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Quantum Control Processor

Architecture

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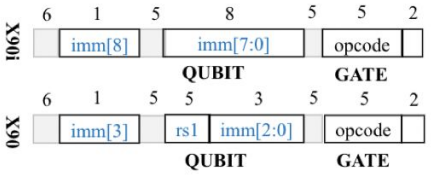
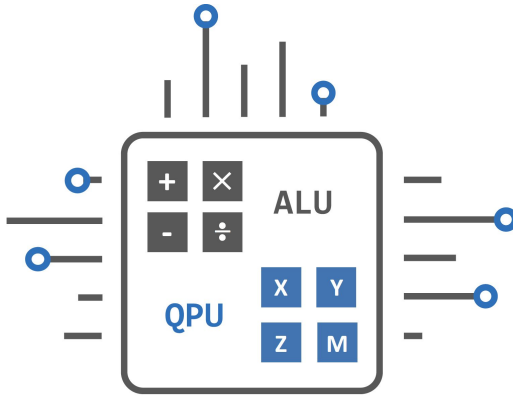
QUASAR: quantum extension for RISC-V

We proposed:

- QUAntum instruction Set ARcitecture (**QUASAR**) extension to the widely used open source RISC-V architecture.



X90i	QUBIT_I;
ADDI	x3, 0, QUBIT_MASK;
Y180	x3;
CNOT	QUBIT_I_0, QUBIT_I_1;
TSi	TIME_STAMP;



QUASAR Ice – extended RV32 core

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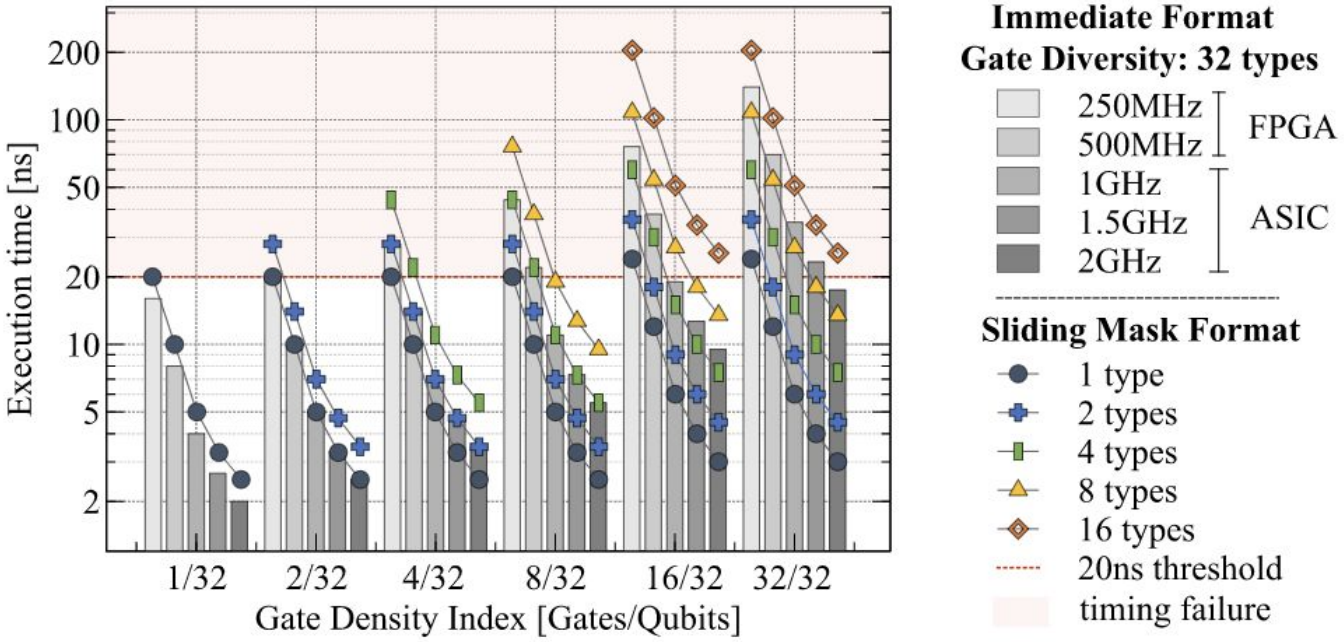
Timing Constraint Satisfaction



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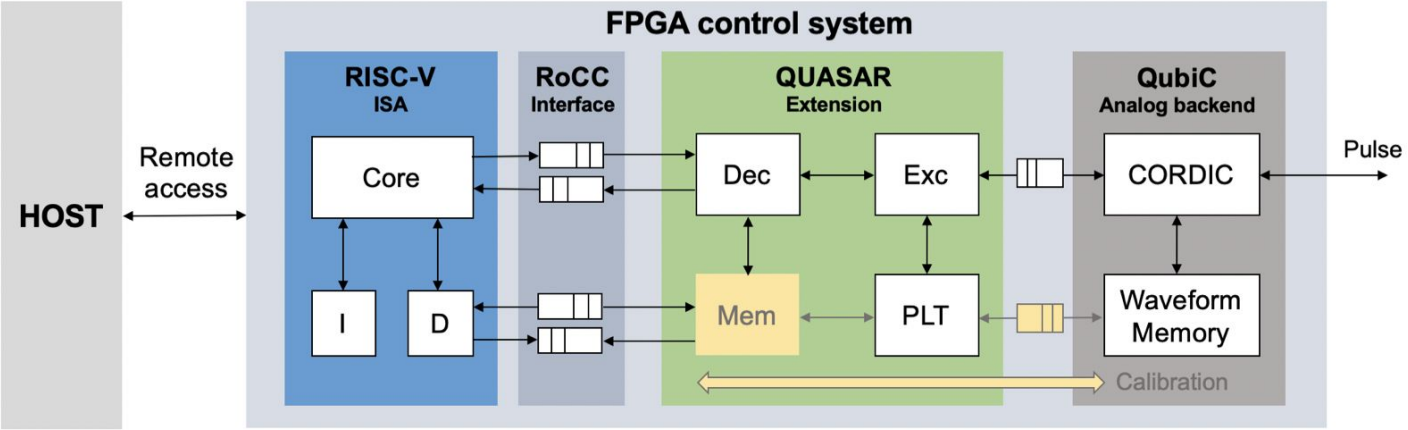
System Architecture Implementation



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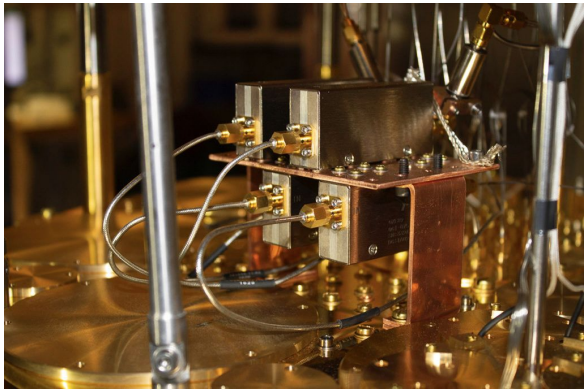
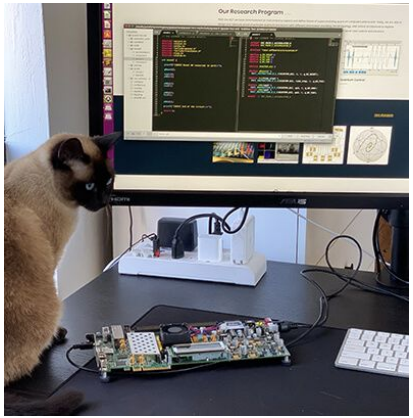
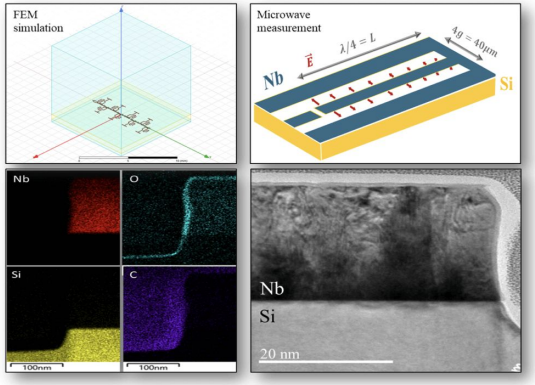
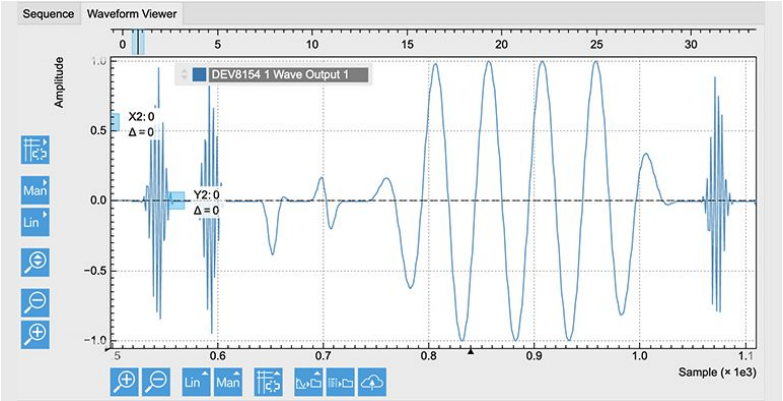





FEM simulation
Microwave measurement
λ/4 = L
Ag = 40μm
Nb
Si
Nb
O
Si
C
100nm
100nm
Nb
Si
20 nm


Sequence
Waveform Viewer
DEV8154 1 Wave Output 1
Amplitude
X2: 0
Δ = 0
Y2: 0
Δ = 0
Man
Lin
Sample (× 1e3)

Advanced Quantum Testbed

https://berkeleyquantum.org

- arXiv:1909.11719
- open-source release

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Thank you for your attention.
Questions?

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