QC and HPC: the Path from the Experimental to Routine Computing

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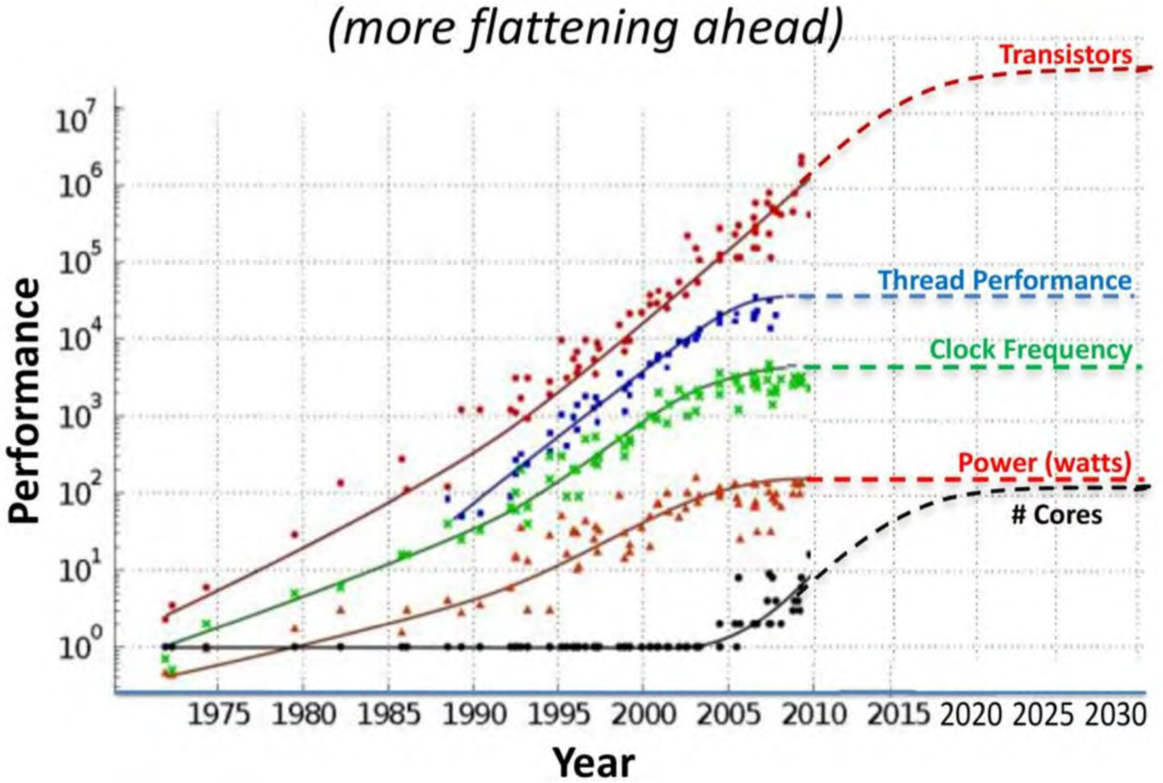
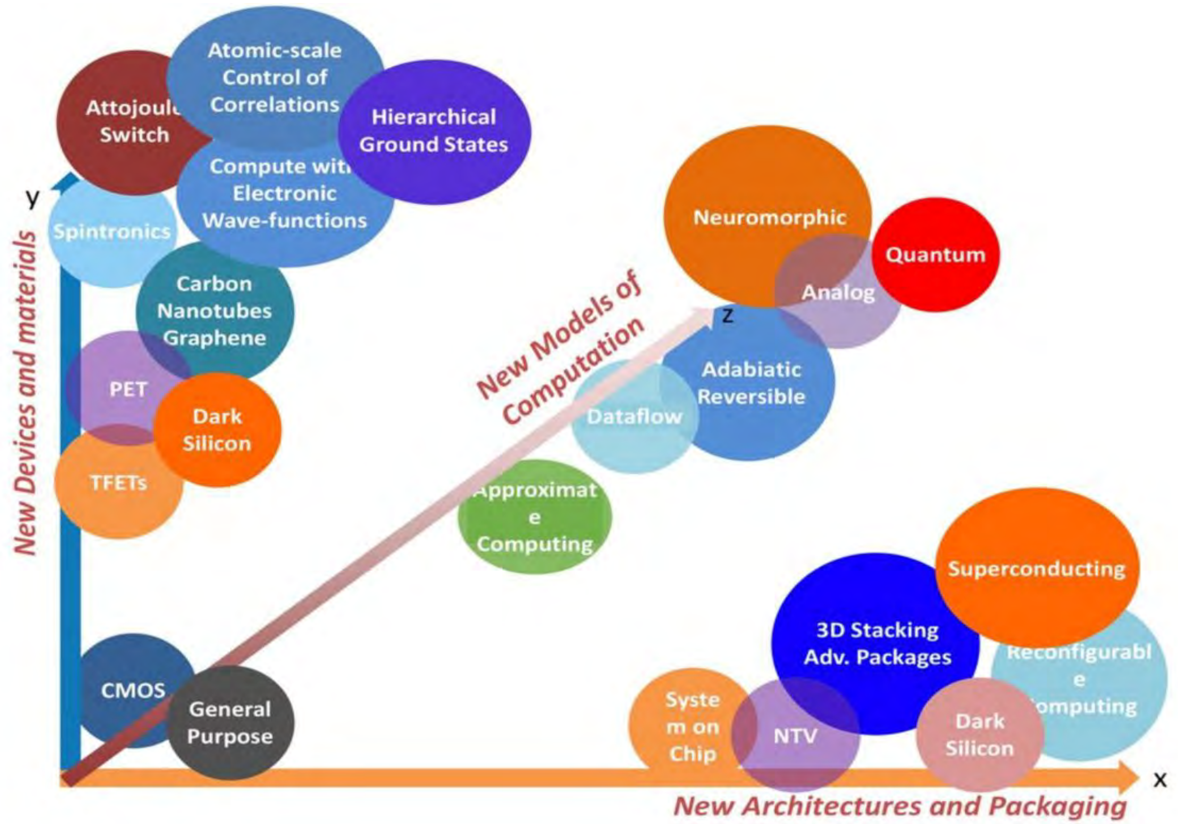
Moore's Law Scaling



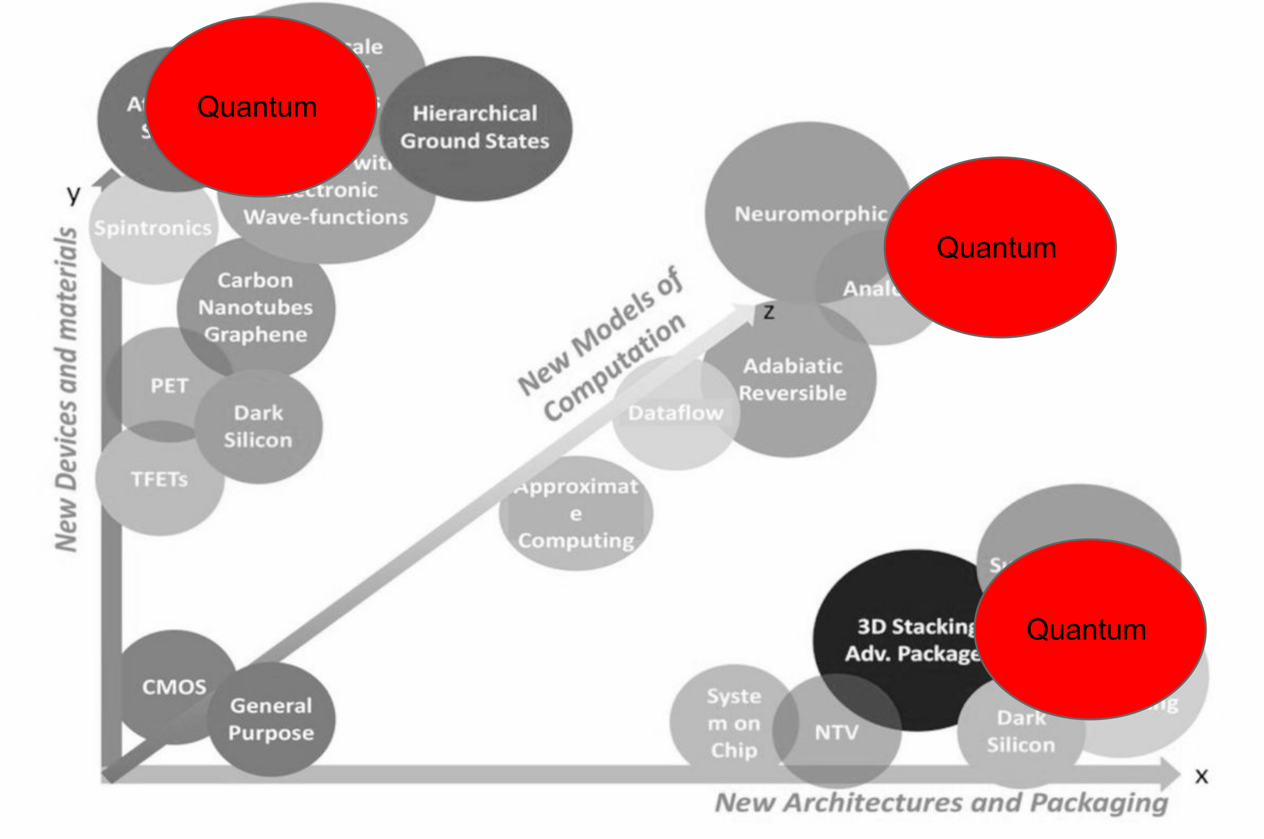
Source: Courtesy of Kunle Olukoton, Lance Hammond, Herb Sutter and Burton Smith

Path Forwards



J.Shalf “The future of computing beyond Moore’s Law” 2020

Path Forwards



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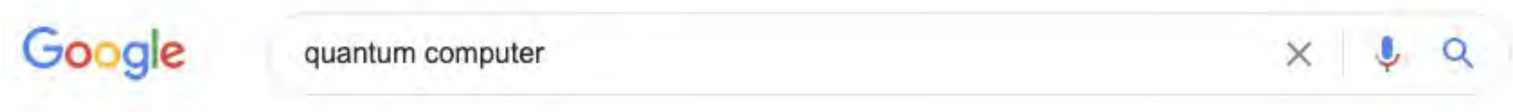
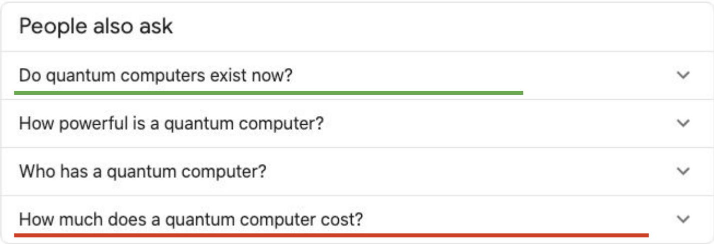
Myth or Reality?



2021



Myth or Reality?

Google

quantum computer

2021

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?

2023

People also ask

- What does a quantum computer do?
- Do quantum computers exist now?
- How long until quantum computers exist?
- Can anyone use a quantum computer?

Feedback

Timeline

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

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

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

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

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

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

2025 — **Financial services** begin to leverage Quantum Computing

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

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

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

2038 - ... — What's next...

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

Moving from experimental to ‘routine’

Experimental vs Routine Computing

- Needs experimentalists/physicists assistance

Experimental vs Routine Computing

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- Focus on the proof of concept, not solving the problem

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- Metrics

Experimental vs Routine Computing

- Needs experimentalists/physicists assistance
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- Metrics
- Lack of standards

Experimental vs Routine Computing

- Needs experimentalists/physicists assistance
- Focus on the proof of concept, not solving the problem
- Metrics
- Lack of standards
- Complex environments
- ...

Challenges

Quality

Quality of Qubits

Extremely sensitive to noise

- from outside environment
- from neighboring qubits
- from unknown sources

→

Research directions

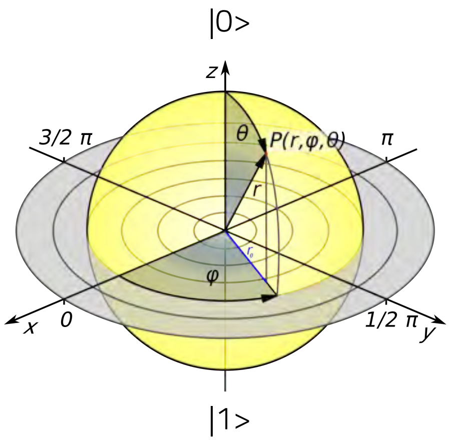
- noise modeling
- noise mitigation
- qubit isolation

remove

- error correction

ignore

Bloch sphere



Quality of Qubits

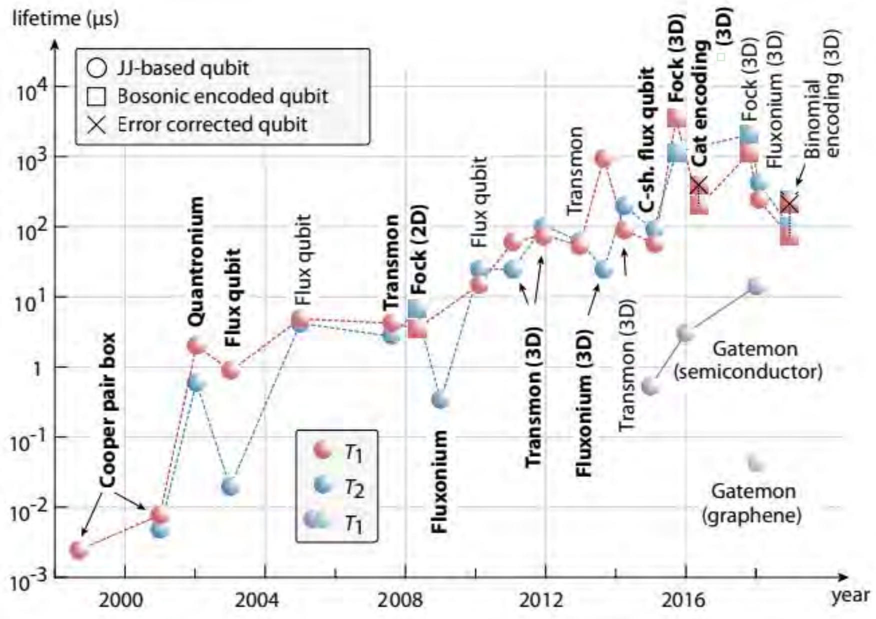
Has limited *lifetime*

- depends on technology

→

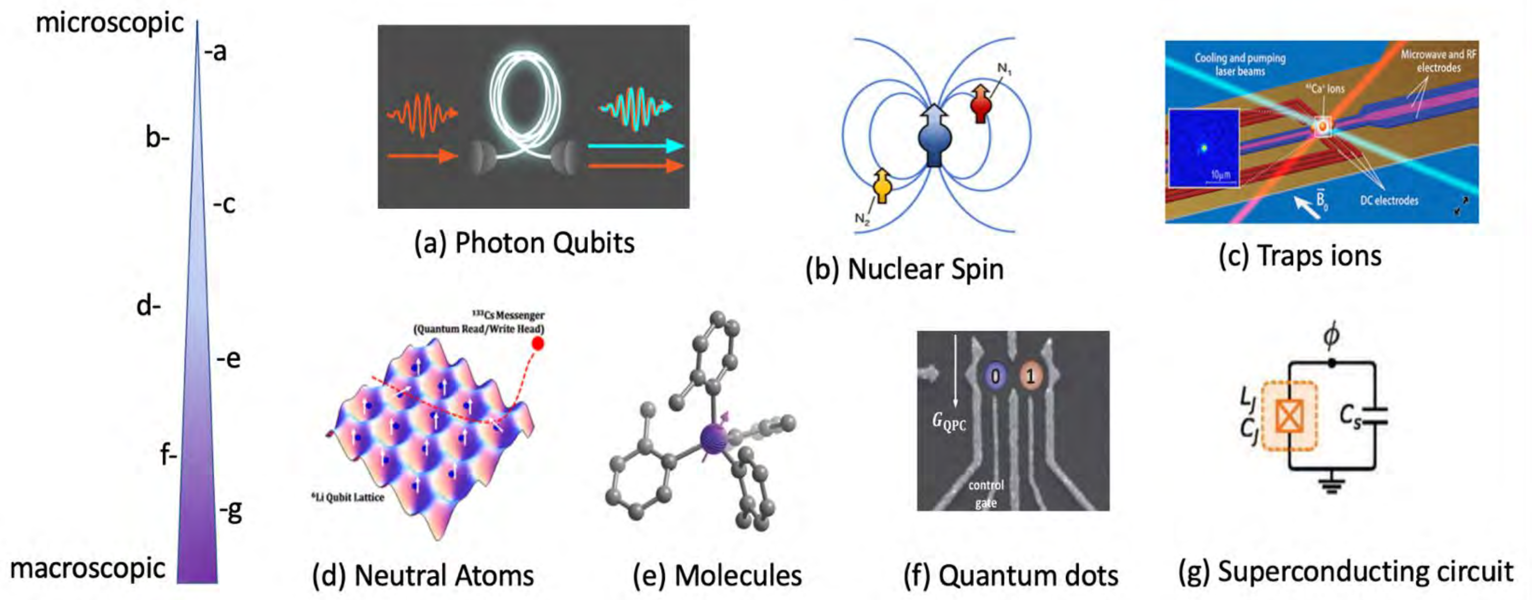
Research directions

- material science/technology



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

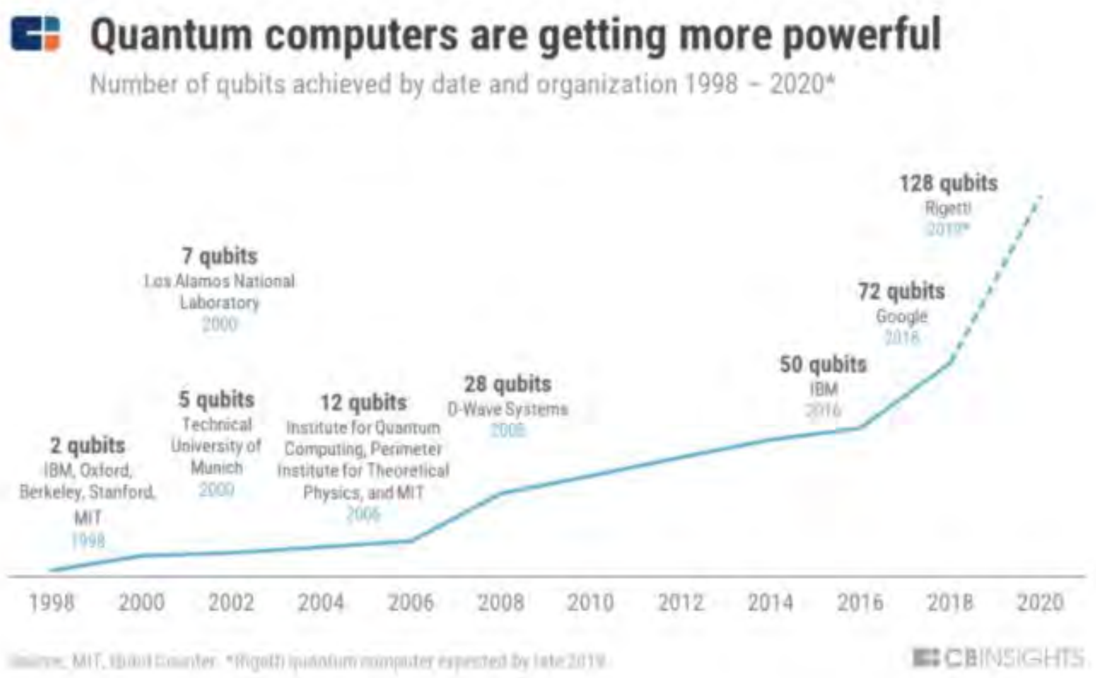
Qubit’s Technology Diversity



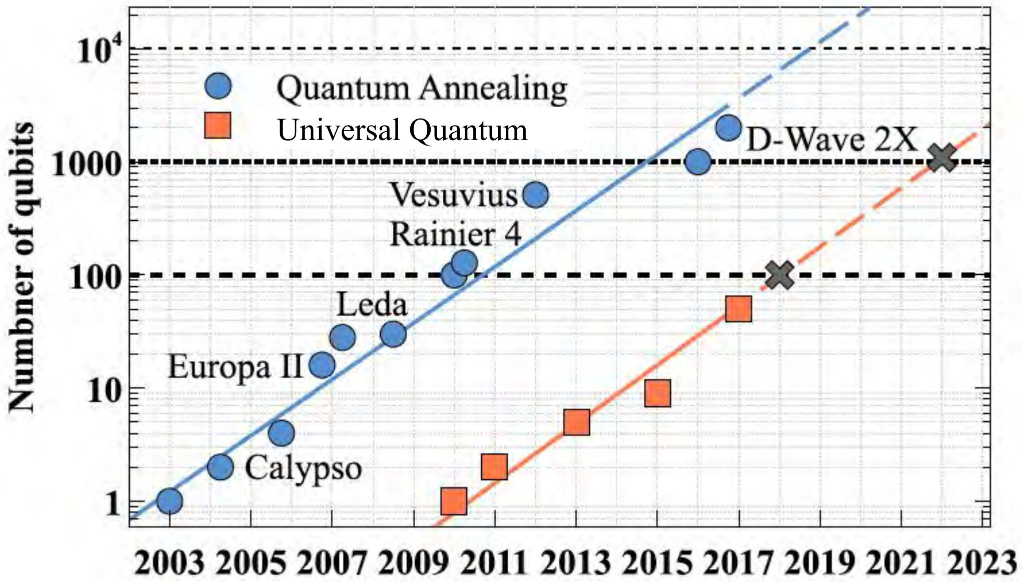
Challenges

Quantity

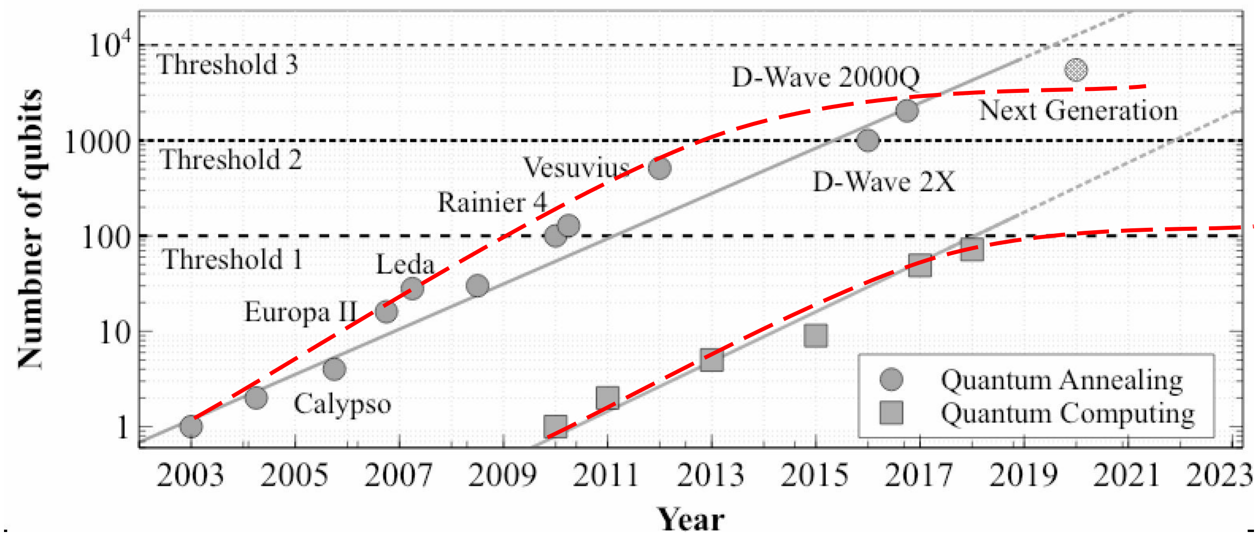
Number of Qubits



Number of Qubits

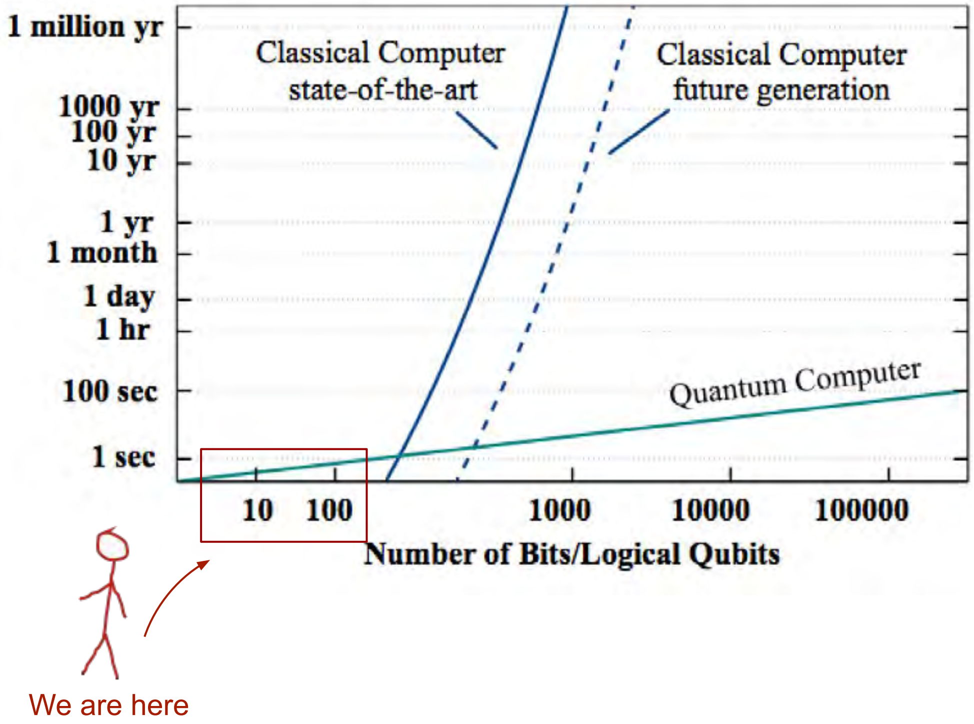


Number of Qubits



The Reality is...

Number factorization problem



Challenges

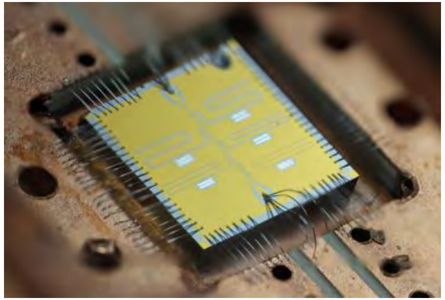
Everything Else

Quantum computer vs. accelerator

Inaccuracy of terminology

- Quantum computer ≠ Quantum Processor

≠



Advanced Quantum Testbed (AQT)

- DOE funded cross-disciplinary project
  - quantum physicists (QNL, MIT LL)
  - material scientists (MF)
  - computer scientists (CRD)
  - engineers (ATAP)
  - industry partners

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Controls, controls, and more controls…

Zurich Instruments

QUASAR/ QubiC 1.0

QICK on ZCU-111 & integrated AFE board

- A mixture of commercial and open-source
- Not shown here:
  - Keysight
  - Qblox
  - Etc
- No 'perfect', comprehensive solution to meet all experimental needs.

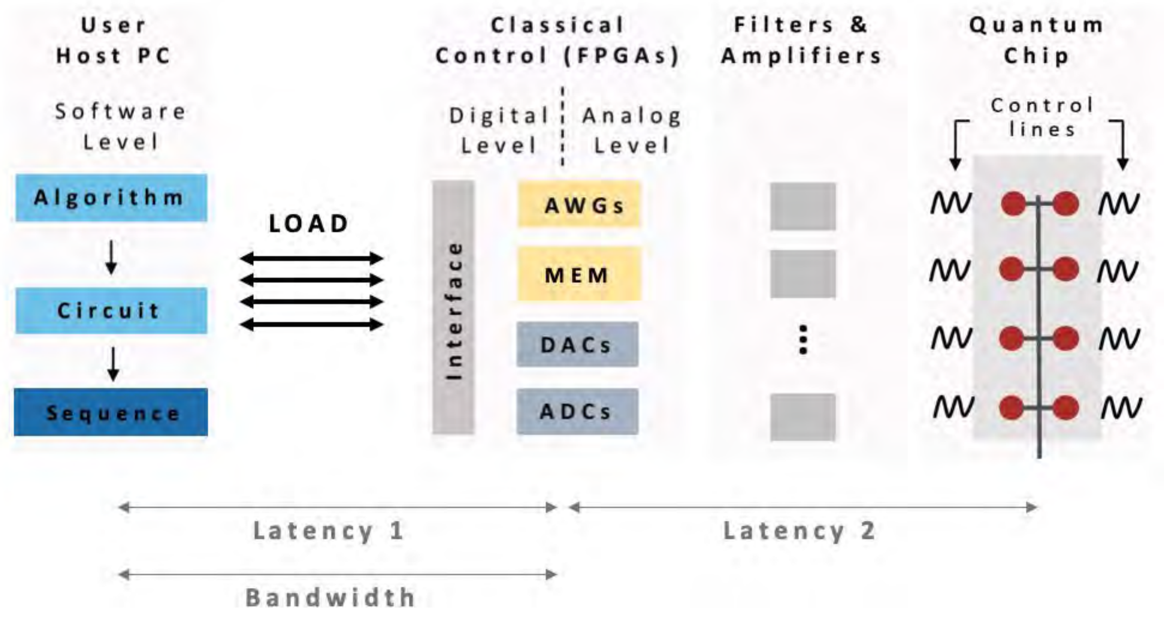
The Control Landscape

- Scaling up existing qubits to systems of 100s-1000s of physical qubits (and more)
- Exploring the novel qubit space and gate-development with 1-2 qubit experiments
- Theorists (and experimentalists alike) proposing experiments requiring more advanced control features (arbitrary feedback/feed-forward schemes, access to the FPGA sandbox)
- Different paths to development; what is the interplay and the role of each?
  - Commercial controls solutions: Keysight, Qblox, Quantum Machines, Zurich Instruments, etc
  - Proprietary integrated controls in industry
  - Open-Source solutions: QICK from Fermilab, QubiC from Berkeley Lab
- Cryogenic controls? Multiplexing? Modularity? Extensibility? What does the 'perfect' control system of the future look like?

Control System

Quantum ISA

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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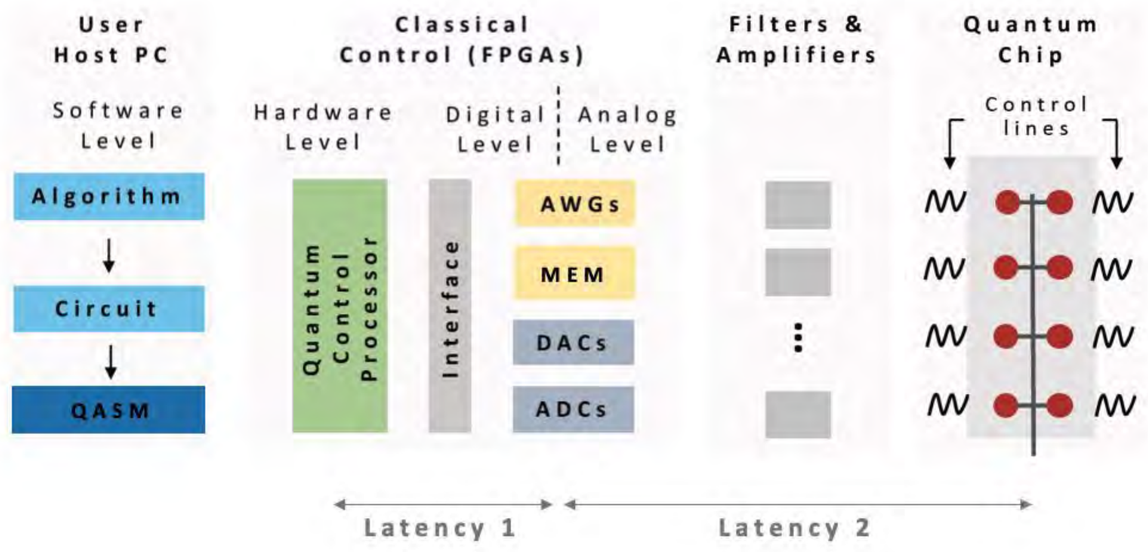
Hardware Control



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

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

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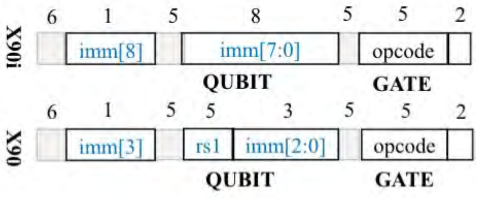
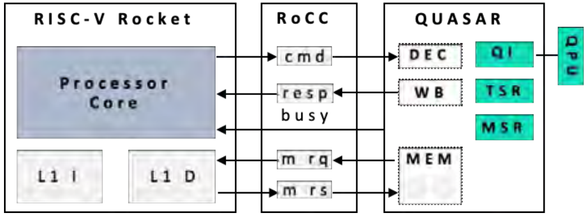
Quantum ISA (QUASAR)

- Quantum Instruction Set Architecture (QUASAR)*
  - extension to RISC-V ISA (open-source, modular, active community, eco-system)
  - supports quantum operations, timing control, etc.
  - transparent, adaptable, open **
- RoCC co-processor adaptation
  - Existing software support
  - Modular approach easily interactable into a big system
  - Low-level customization and flexibility




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



* A. Butko, et al. "Understanding quantum control processor capabilities and limitations through circuit characterization". IEEE ICRC (2020)

** https://ipo.lbl.gov/quantum-instruction-set-architecture-quasar/

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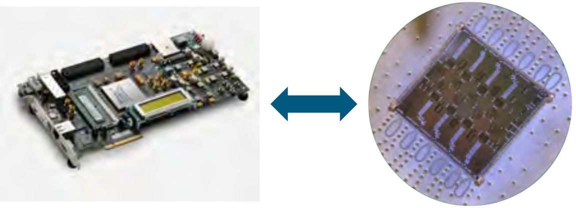
Experiments with the Quantum Processor

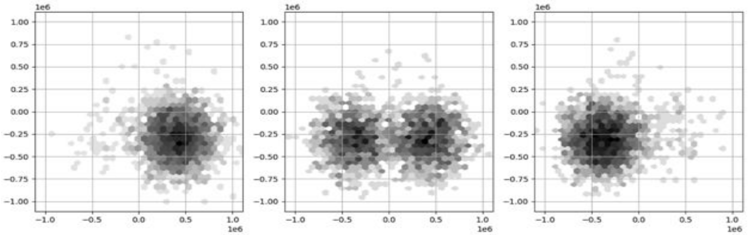
Experimental Setup:

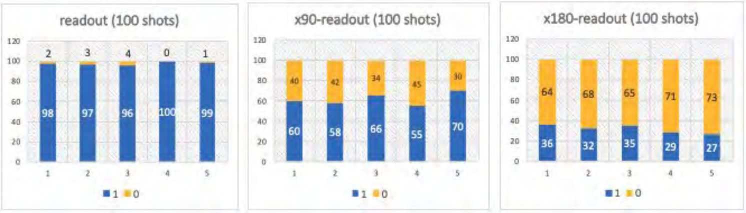
- VC707 FPGA connected to the fridge with the Berkeley QP
- QUASAR-based system deployed on FPGA
- Linux OS running quantum algorithms



Fast Feedback Demo:

- Mid-circuit measurement
- Statistically significant data collection
- Conditional branching at runtime



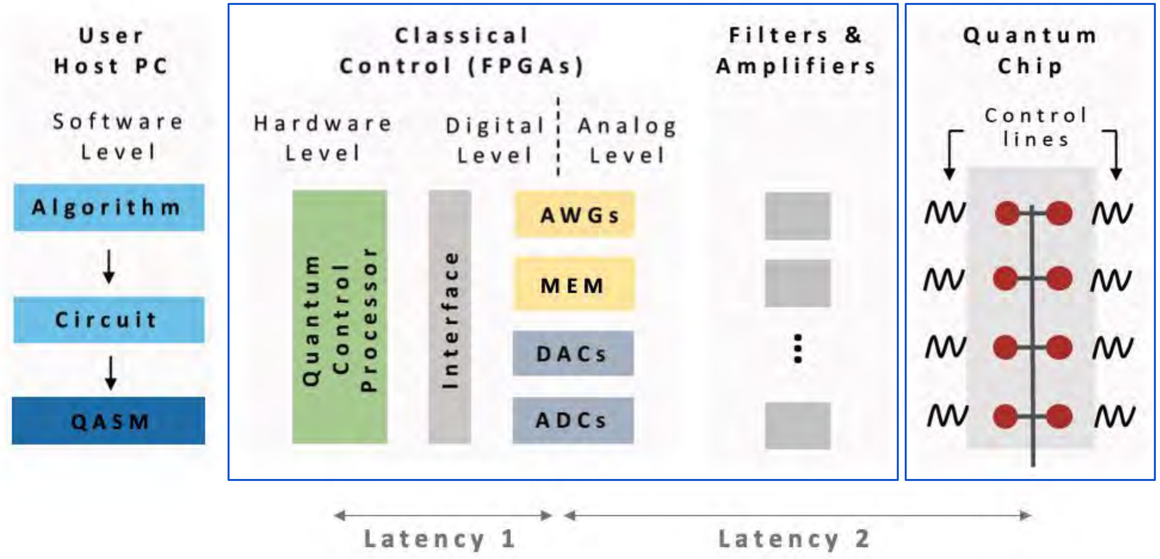


Future Systems

Low-Temperature Control

Hardware Control

What about this? Low temperature



- Reduced latency further ✅
- Super Fast feedback ✅
- Integrated scalability ✅
- Far Beyond-NISQ ✅

- Potential noise ❌
- Requires new technologies ❌
- New architectures ❌

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New Trends: Low-temperature Technologies

B. Patra et al., "**A Scalable Cryo-CMOS 2-to-20GHz Digitally Intensive Controller for 4×32 Frequency Multiplexed Spin Qubits/Transmons in 22nm FinFET Technology for Quantum Computers,**" 2020 IEEE International Solid-State Circuits Conference - (ISSCC), 2020

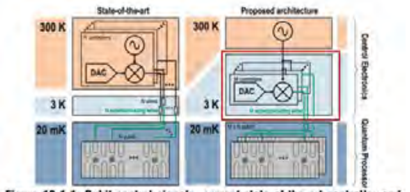
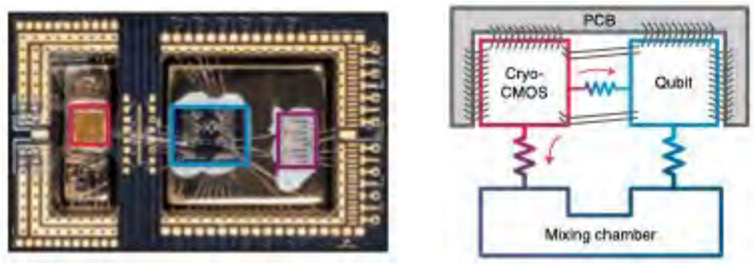
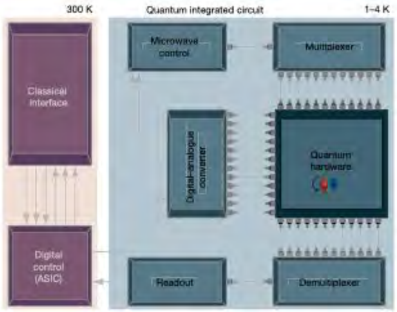


Figure 19.1.1: Qubit control signals, current state-of-the-art controller and presented cryogenic controller with frequency multiplexing.

S. J. Pauka et al., "**A cryogenic cmos chip for generating control signals for multiple qubits**," Nature Electronics, 2021.



L. Petit et al., "**Universal quantum logic in hot silicon qubits**," Nature, 2020.

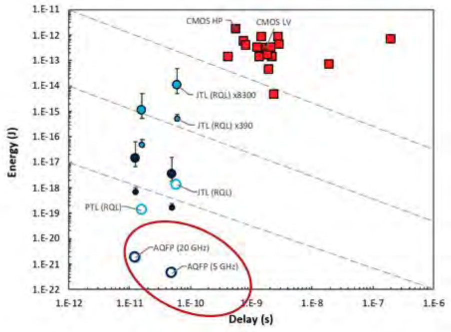


Noise Budget
Power Budget
Monolithic Integration

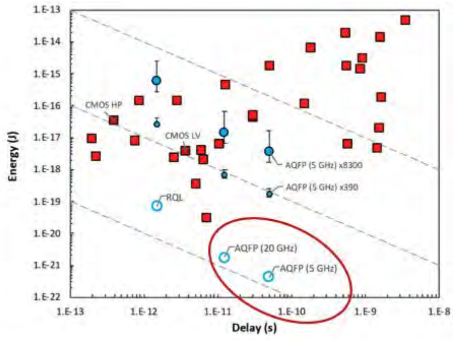
Adiabatic Quantum-Flux-Parametron (AQFP)

- Energy-Efficient Circuits *
- Dynamic energy dissipation is reduced due to the adiabatic switching operations using AC excitation currents
- AQFP could overcome the power/energy dissipation limitation in conventional superconductor logic families such as rapid-single-flux-quantum (RSFQ)

* Chen, O. et al. “Adiabatic Quantum-Flux-Parametron: Towards Building Extremely Energy-Efficient Circuits and Systems.” Scientific Reports 9 (2019): n. pag.



CEQIP-4 Energy versus Delay for Interconnects of 1 mm Length



CEQIP-3 Energy versus Delay for Intrinsic Elements

Circuit Complexity

** Cryogenic Electronics and Quantum Information Processing,” IEEE International Roadmap for Devices and Systems, 2020IRDS_CEQIP, 2020. https://irds.ieee.org/editions/2020

Superconducting Logic Research

Opportunity: ***Low power, ultra-high performance computing***

- 600+GHz clock frequencies demonstrated in lab for superconducting RSFQ logic
- Lossless electrical data transmission
- Lower power (even with cryo-refrigeration taken into account)

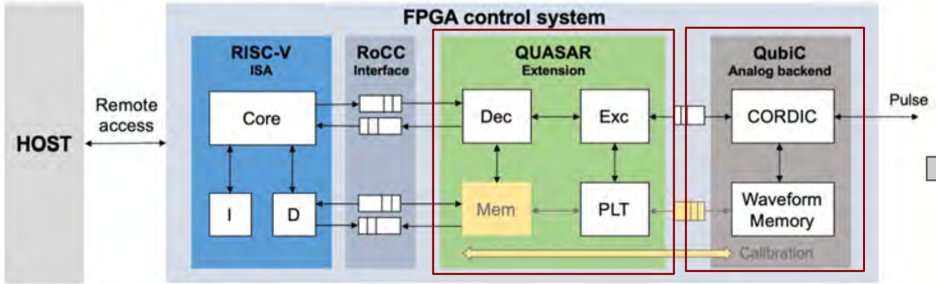
Active Research Directions

- **SuperTools**: Develop superconducting variant of RISC-V processor to evaluate emerging Superconducting Electronic Design Tools for iARPA.

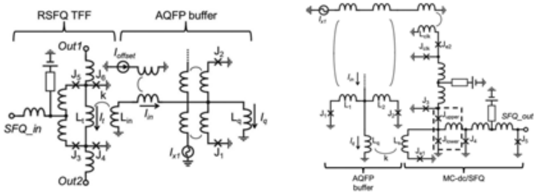
Produce examples that will generate interest from potential stakeholders (that make use of the SuperTools EDA)

- Dataflow CGRA for streaming DSP (many uses)
- Temporal Logic
- **Quantum Control (QUASAR)**

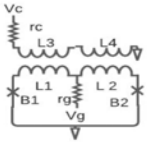
Low-temperature Control



F. China et al., “Design and Demonstration of Interface Circuits Between Rapid Single-Flux-Quantum and Adiabatic Quantum-Flux-Parametron Circuits”, 2016



Voltage-to-Frequency ADC



AQFPBlock	Runtime	Base Model			Majority Model		
		Delay	JJ Count	Energy	Delay	JJ Count	Energy
Counter	<1s	12	144	720 zJ	12	126	630 zJ
Memory 1KiB	4d3h30m	64	2001576	10 fJ	56	1793942	8.97 fJ
Reg File 8x8	4s	20	8164	40.82 aJ	20	8246	41.23 aJ
Buffer	19s	36	41334	207 aJ	32	35508	178 aJ
QUASAR	5d19h29m	108	789416	3.95 fJ	108	786680	3.93 fJ

Credit to Darren Lyles and Meriam Bautista

~~Moving~~ from experimental to 'routine'

Enabling 'routine' computing, continuing experimenting

Thank you for your attention.
Questions?

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