Intro and Motivation: Closing the Gap Between Quantum Algorithms and Hardware through Software-Enabled Vertical Integration and Co-Design

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an NSF Expedition in Computing

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Tutorial Schedule

- 1:00 - 1:15 Install Tutorial Software
- 1:15 - 1:45 Intro and Research Challenges (Fred Chong)
- 1:45 - 2:40 Tools for QC Arch Research (Margaret Martonosi)
- 2:40 - 3:00 Quantum Basics and Alg Demo (Ali Javadi-Abhari)
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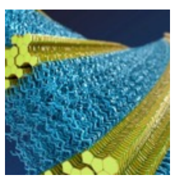
Why Quantum Computing?

- Fundamentally change what is computable
  - The only means to potentially scale computation exponentially with the number of devices
- Solve currently intractable problems in chemistry, simulation, and optimization
  - Could lead to new nanoscale materials, better photovoltaics, better nitrogen fixation, and more

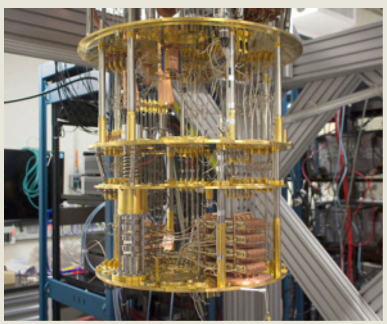


- A new industry and scaling curve to accelerate key applications
  - Not a full replacement for Moore's Law, but perhaps helps in key domains
- Lead to more insights in classical computing
  - Previous insights in chemistry, physics and cryptography
  - Challenge classical algorithms to compete w/ quantum algorithms

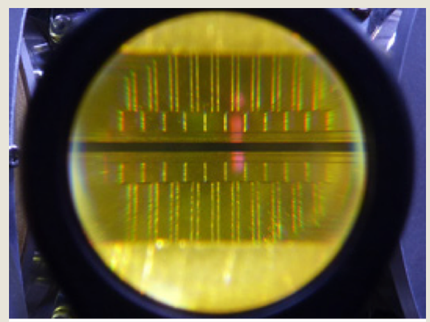
NISQ

Now is a privileged time in the history of science and technology, as we are witnessing the opening of the NISQ era (where NISQ = noisy intermediate-scale quantum).

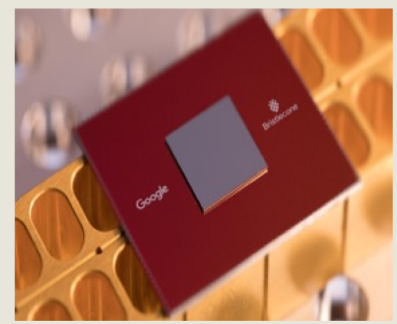
– John Preskill, Caltech



IBM
50 superconductor qubits

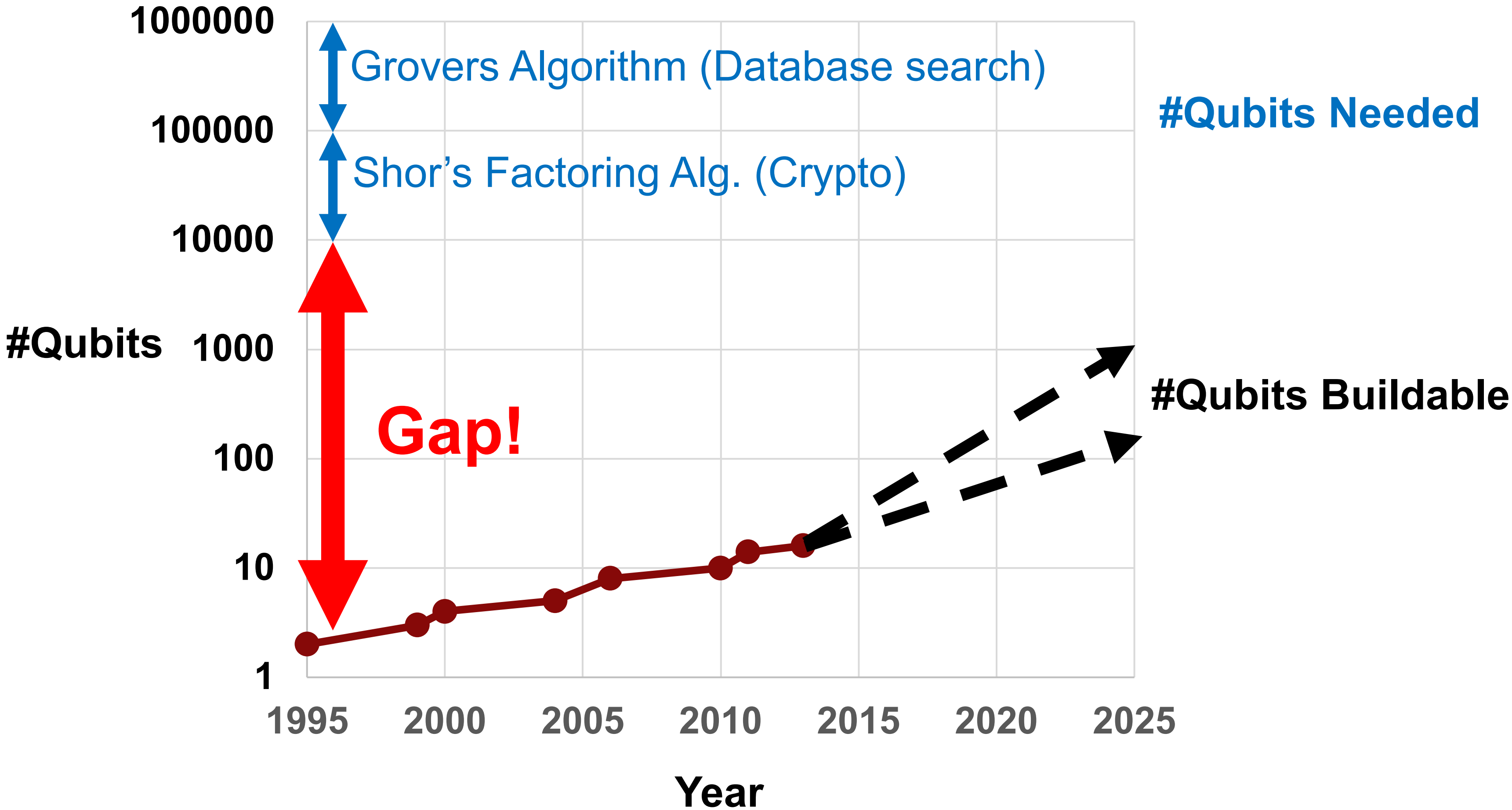


Innsbruck
20 atomic ion qubits

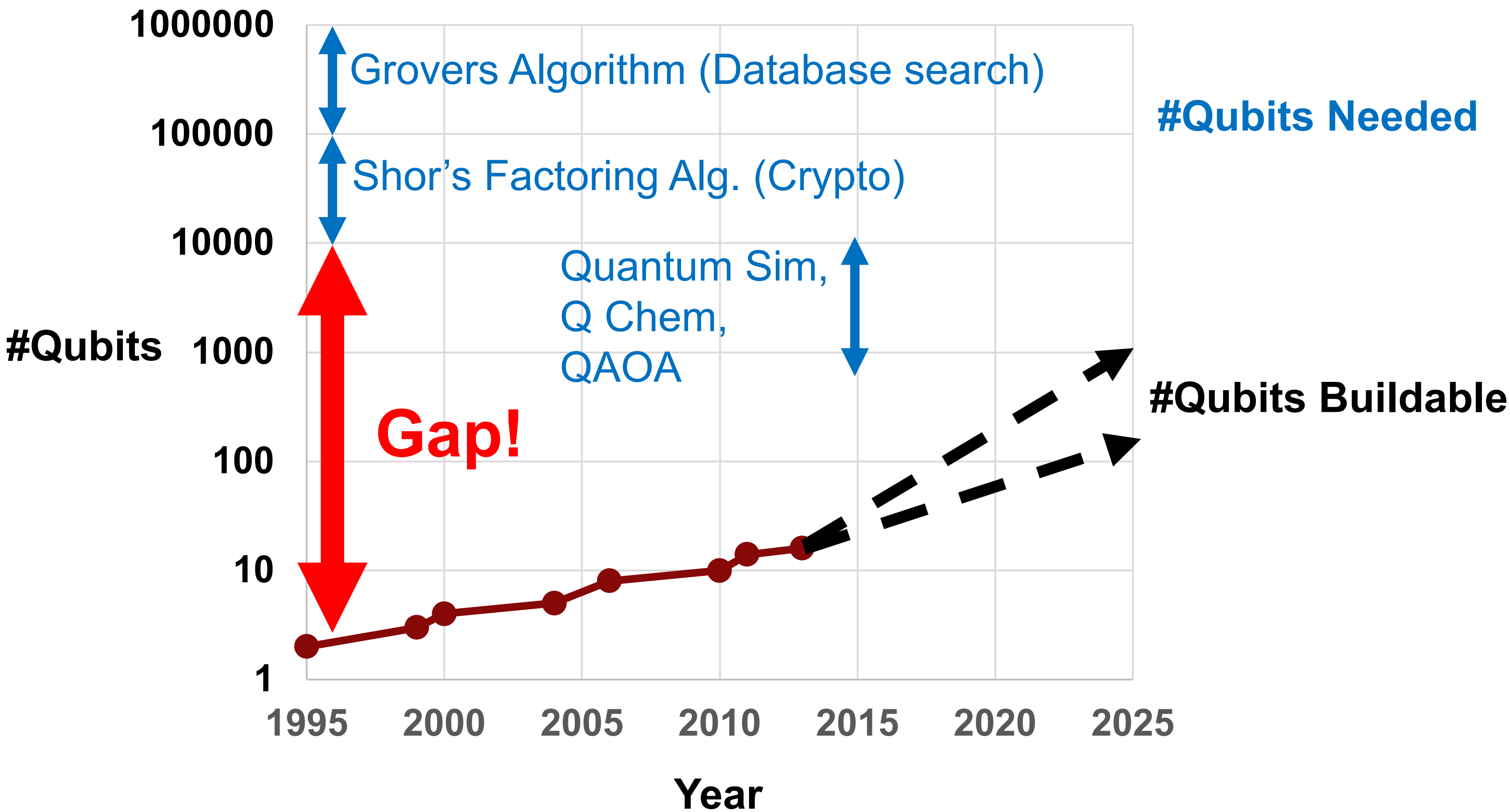


Google
72 supercond qubits

The Algorithms to Machines Gap



The Algorithms to Machines Gap



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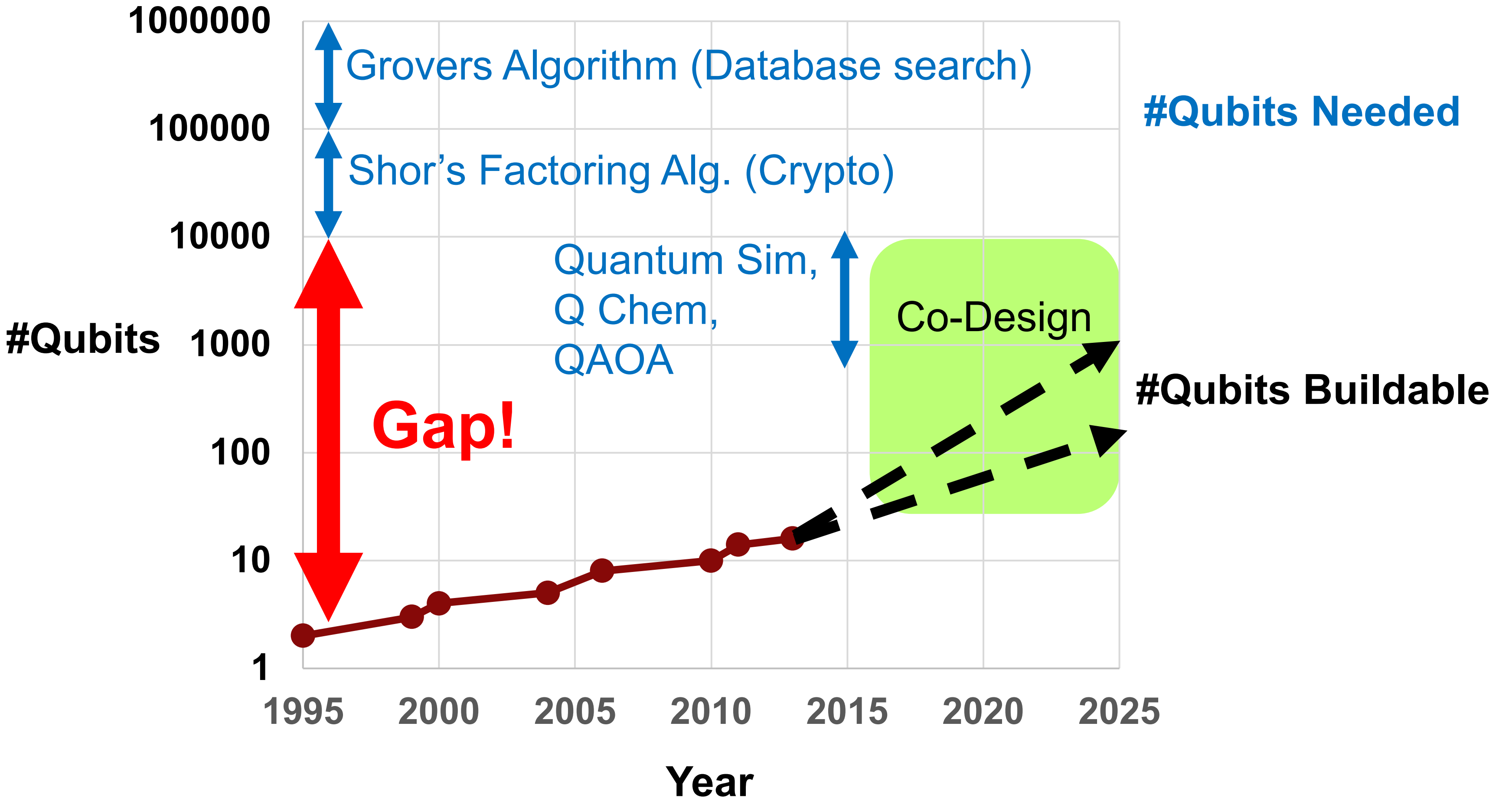
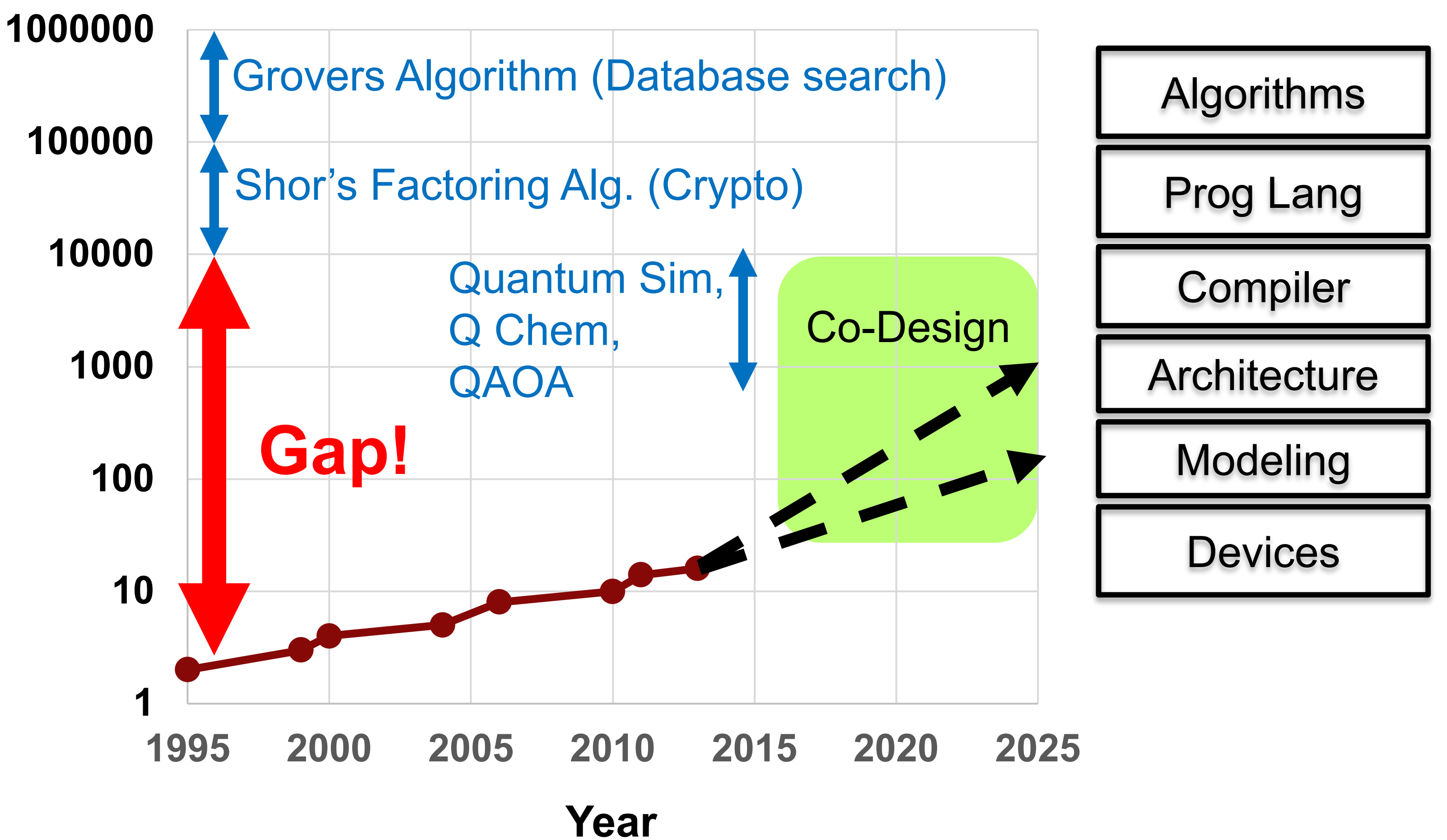
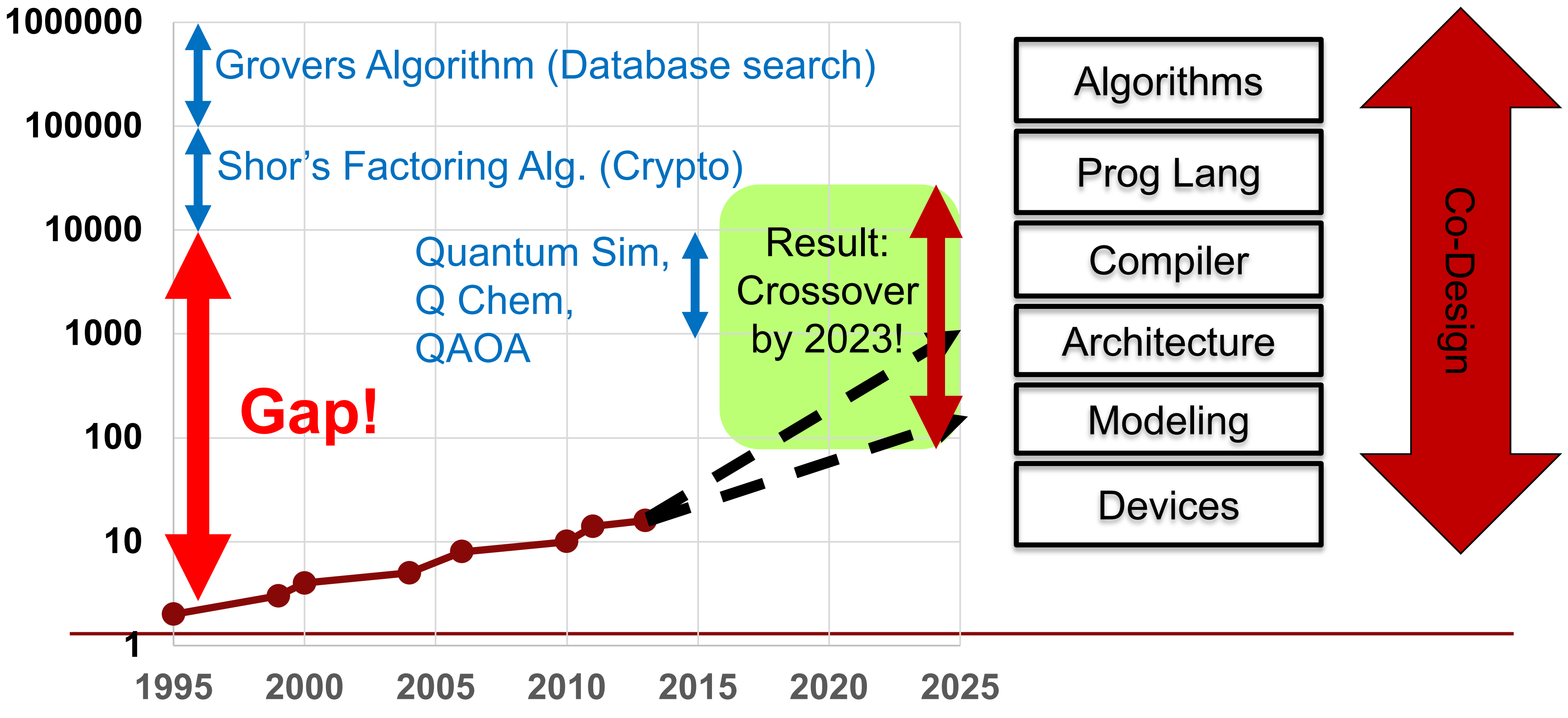


Closing the Gap: Software-Enabled Vertical Integration and Co-Design

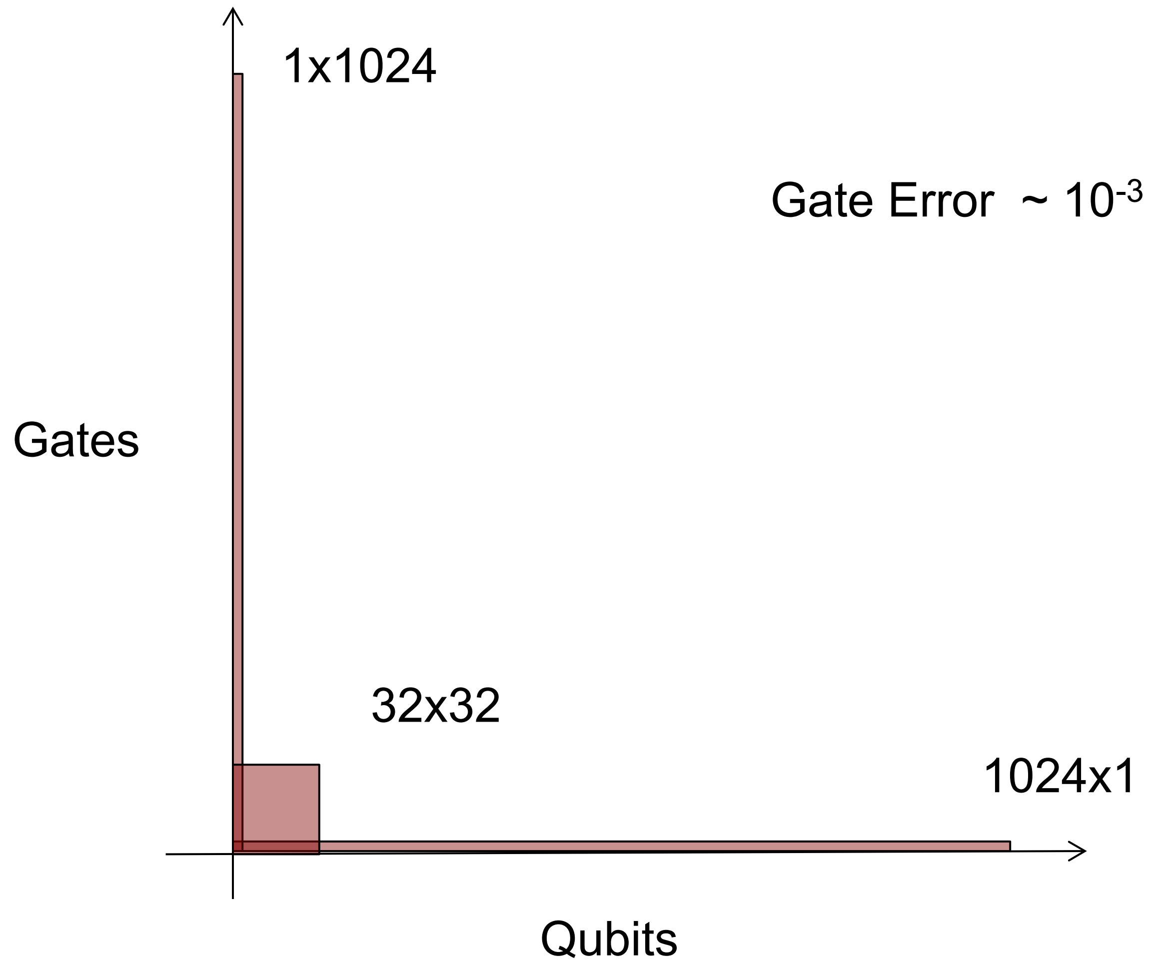


Goal

Develop co-designed algorithms, SW, and HW to close the gap between algorithms and devices by 100-1000X, accelerating QC by 10-20 years.



Space-Time Product Limits



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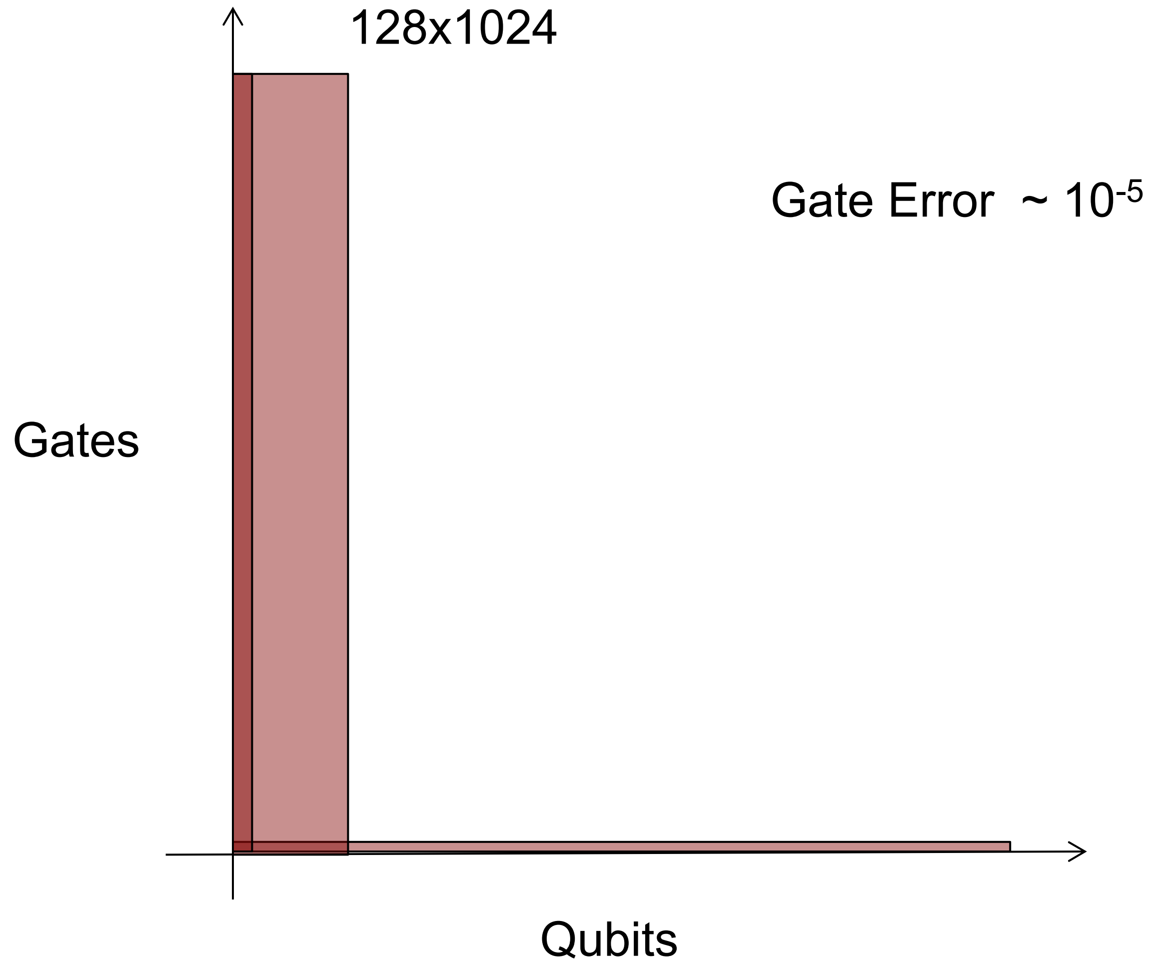
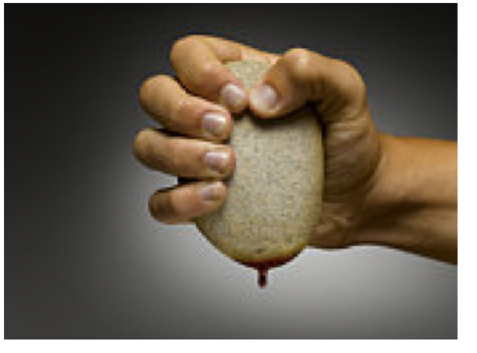


"Good" Quantum Applications

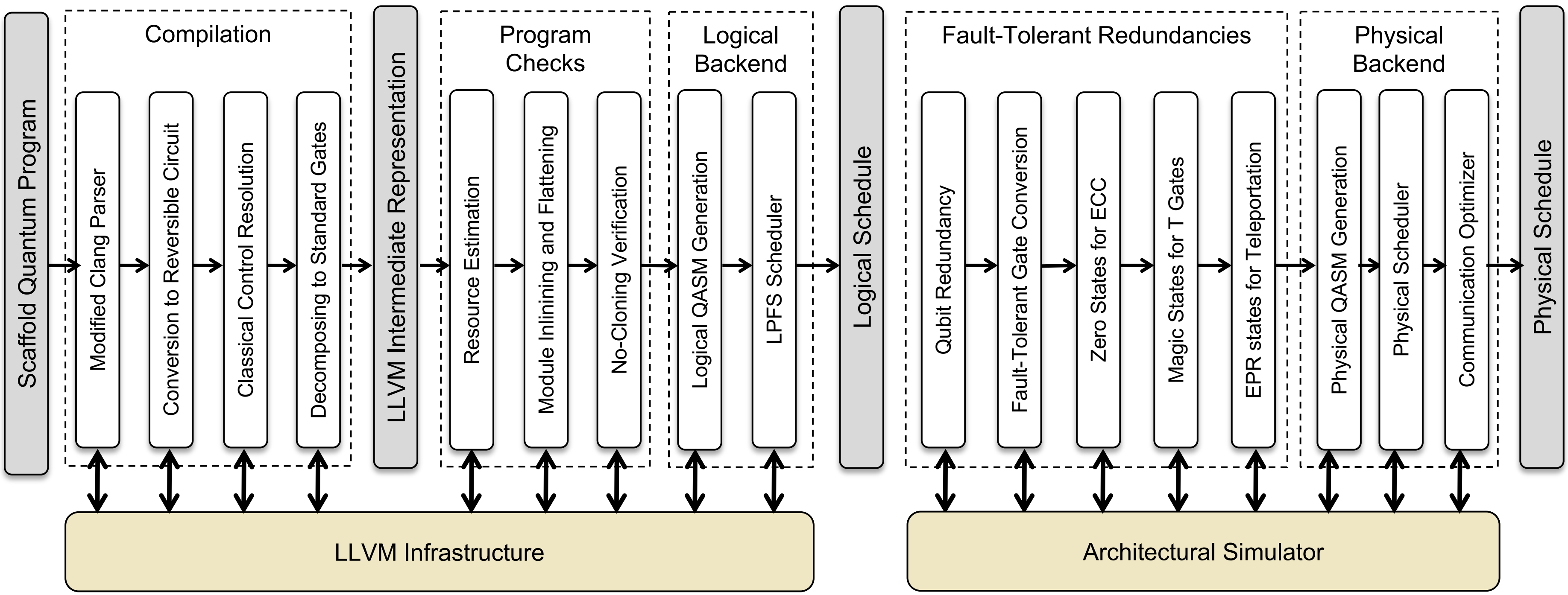
- Compact problem representation
  - Functions, small molecules, small graphs
- High complexity computation
- Compact solution
- Easily-verifiable solution
- Co-processing with classical supercomputers
- Can exploit a small number of quantum kernels

Quantum Compiler Optimizations

- Similar to circuit synthesis for classical ASICs
- Program inputs often known at compile time
- Manage errors and precision
- Scarce resources
  - Every qubit and gate is important



Tool Flow



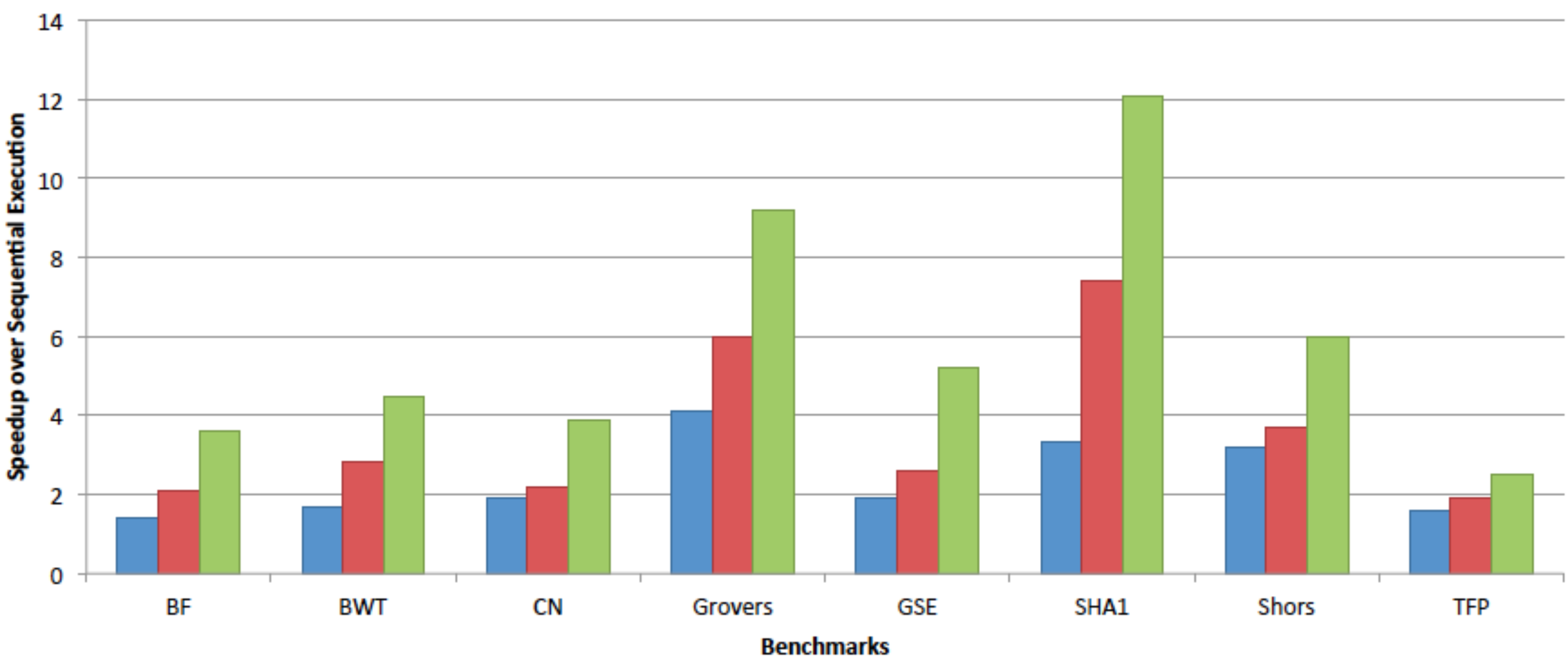
Scaffold tools, 41K lines of code, open source
epiqc.cs.uchicago.edu

https://github.com/epiqc/ScaffCC

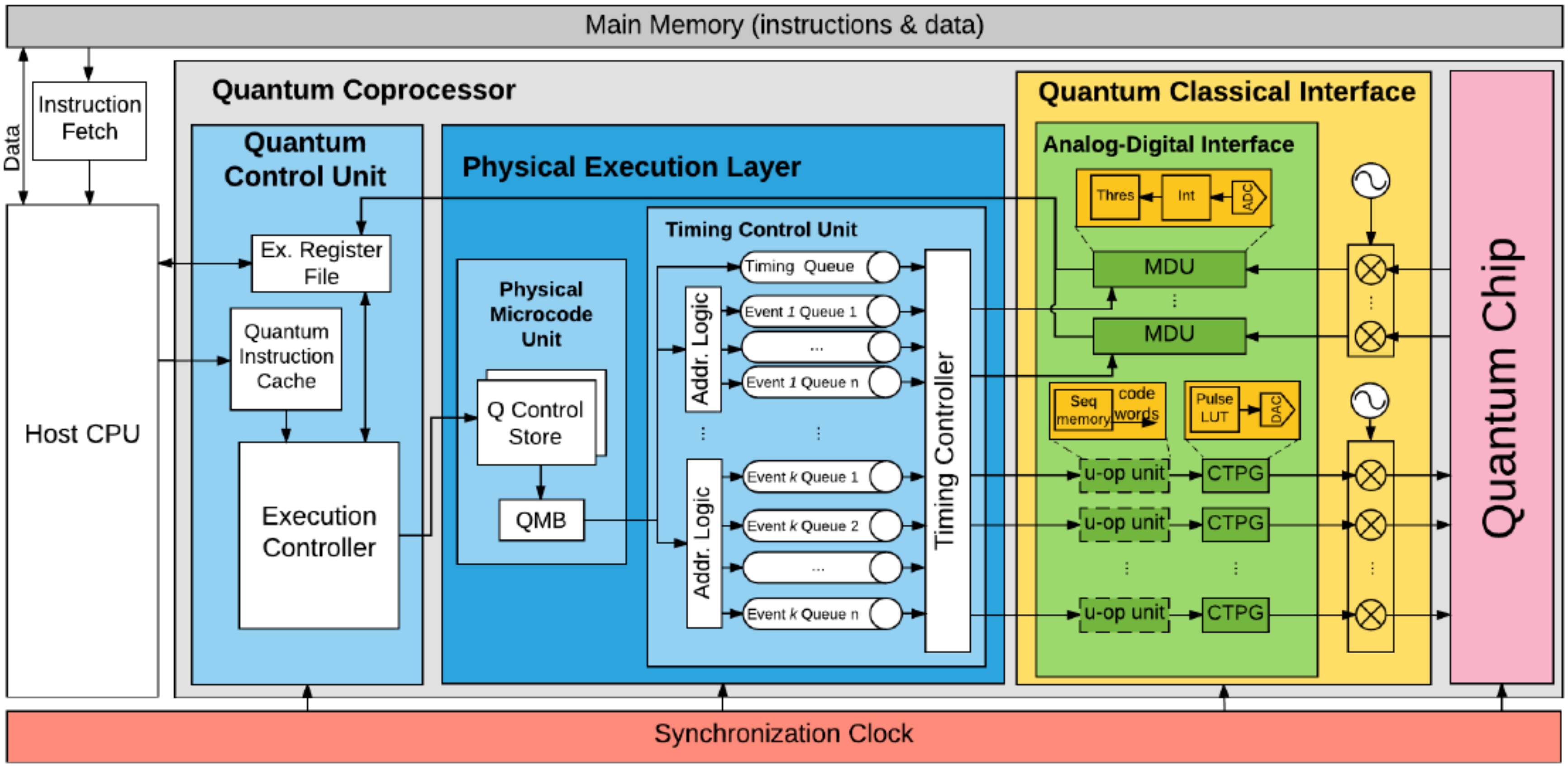
Increasing Parallelism

- Compiler Optimizations:
  - Loop unrolling, constant propagation, inlining, function cloning, DAG scheduling

[Heckey+ ASPLOS 2015]

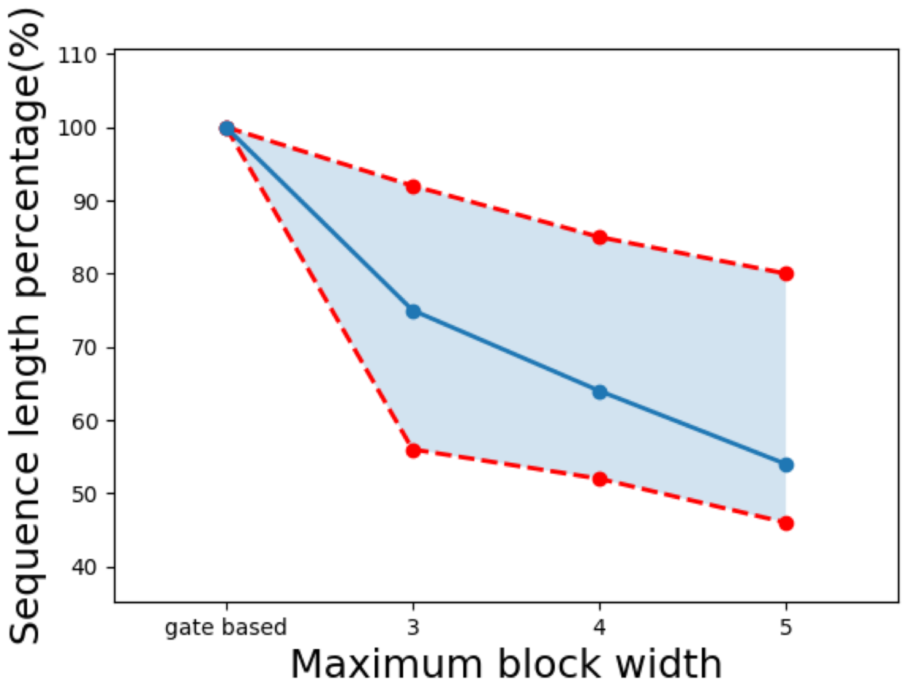


Microarchitecture



[Fu+ Micro 2017 Best Paper]

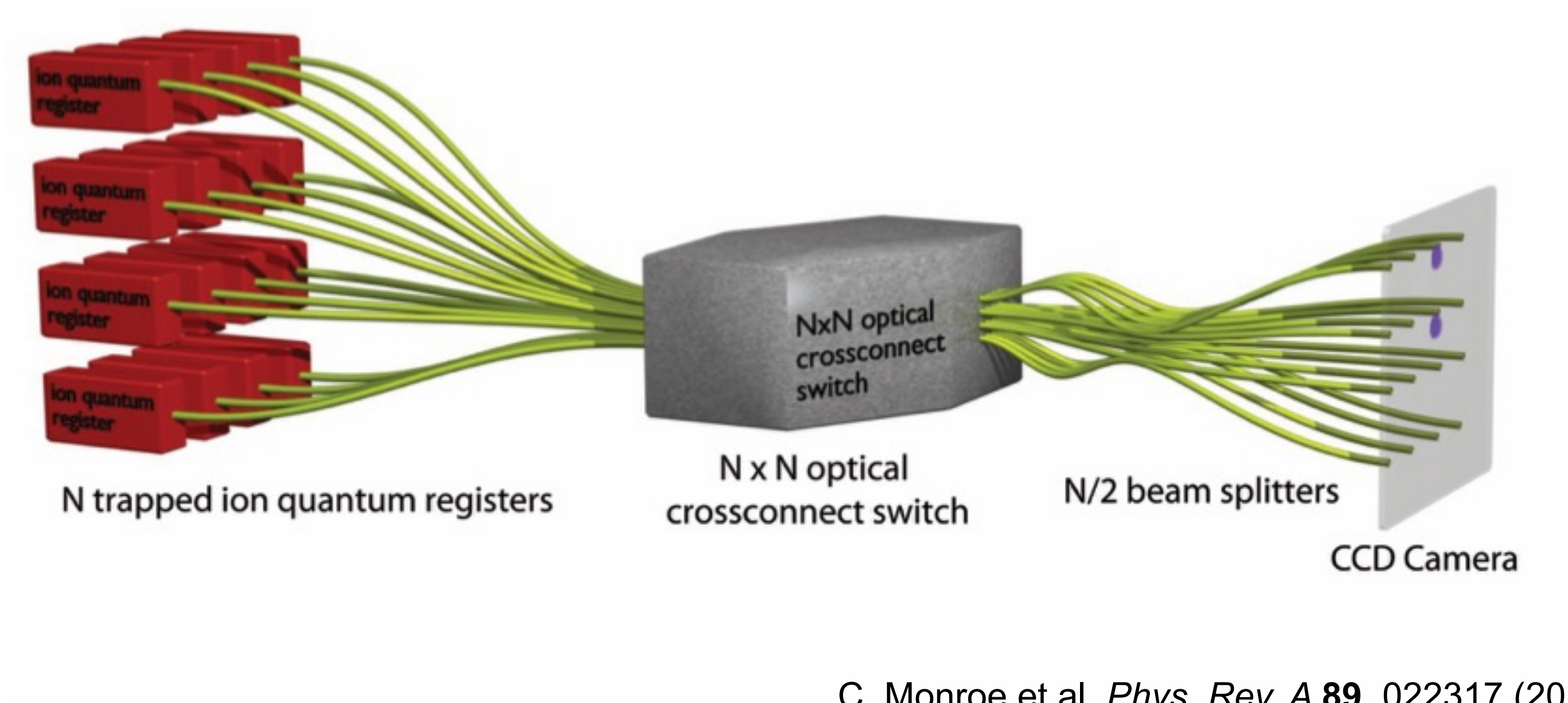
Breaking ISA Abstraction



- Multi-Qubit Operators for QAOA
  - Direct translation from compiler to control pulses

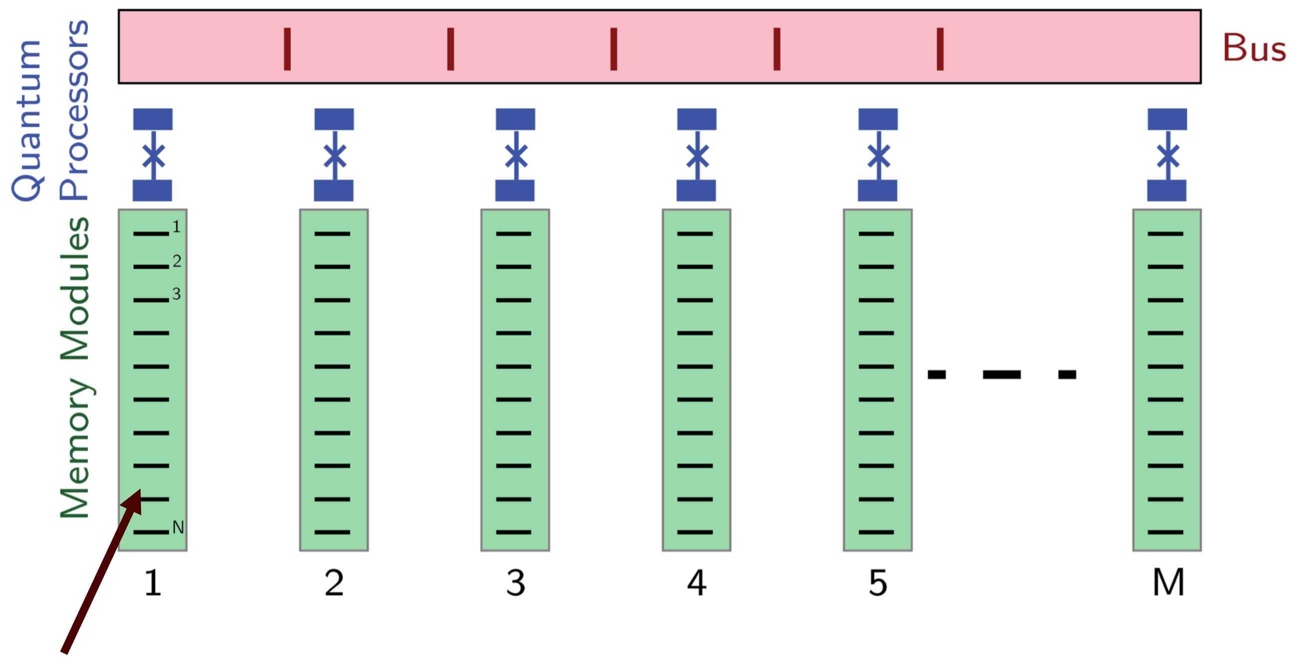
[Joint work with David Schuster]

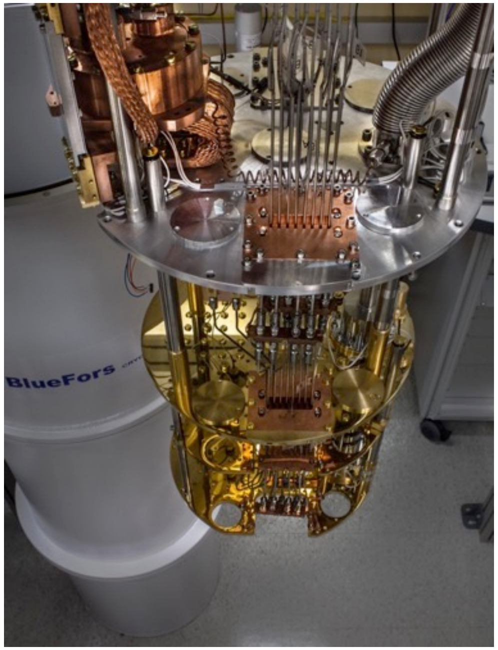
Modularity



C. Monroe et al. *Phys. Rev. A* **89**, 022317 (2014)

Modular Chicago QC Hardware architecture (Schuster)





Each memory mode an hold a qudit with up to 10 states

Advantages:

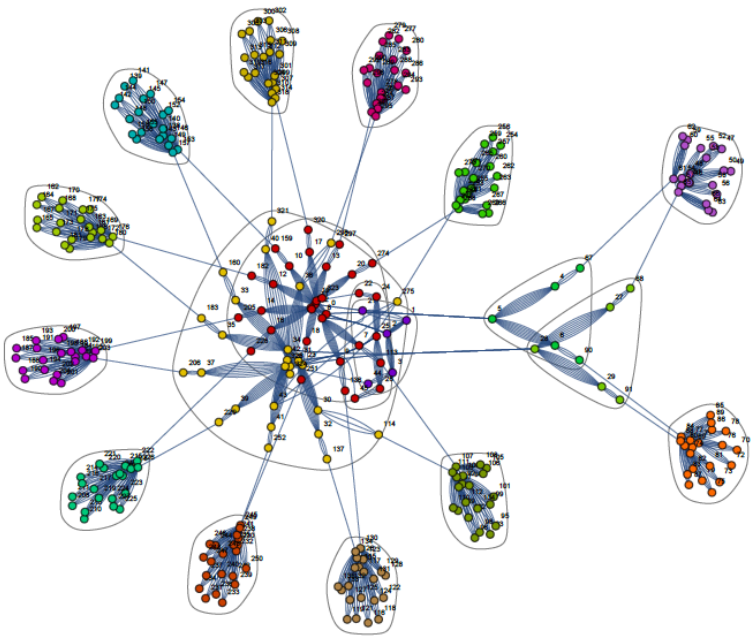
- 10 qubits per module, made in the machine shop, not the cleanroom
- 10x fewer transmons, 10x less classical hardware

Local vs Non-Local Communication

- Maybe 10X bandwidth difference?
- Not that unusual in the classical world
- How does this affect quantum algorithms?

Static vs Dynamic: Mapping Data

- Static spectral and graph partitioners
- Map for clustering
  - Probably necessary to get to 1000 qubits
- Map for irregular physical constraints
  - Qubit couplings, hardware defects
- Granularity of mappings
- Interaction with qubit reuse



Spectral communities for 2-level Bravyi-Haah magic-state factory

Static vs Dynamic: Compilation

- Many applications static
- But quantum-classical co-processing may require dynamic parameters
- How to get a high level of optimization without complete re-compilation?
  - Eg hours for optimal control pulse generation, but how to adapt to changing rotation angles?
  - Similar to partial compilation for FPGAs

Multiple Tech vs Comm Overhead

- Classical architectures composed of multiple technologies: logic, SRAM, DRAM, interconnect
- With optical transduction, we can have:
  - Ions for high connectivity
  - Superconductors for high speed
  - Neutral atoms for storage

Classical Control and Computation

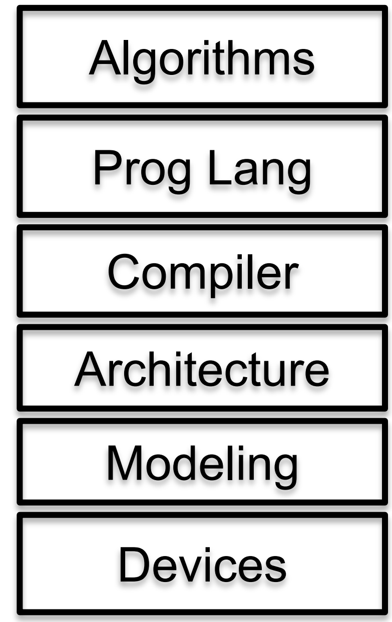
- Temperature boundaries and interconnect constraints [Tannu+ Micro17]
  - Cryo-cmos: high power, but lower cost to cool 4k
  - Superconducting: expensive memory, low power, but expensive to cool to 10mk
- Real-time control: hard for GHz speeds
  - Adaptive algorithms, ML
- Error decoding
  - Fast, simple decoder in superconducting logic
    - Trade frequency of decoding for quality

How do I know if my QC program is correct?

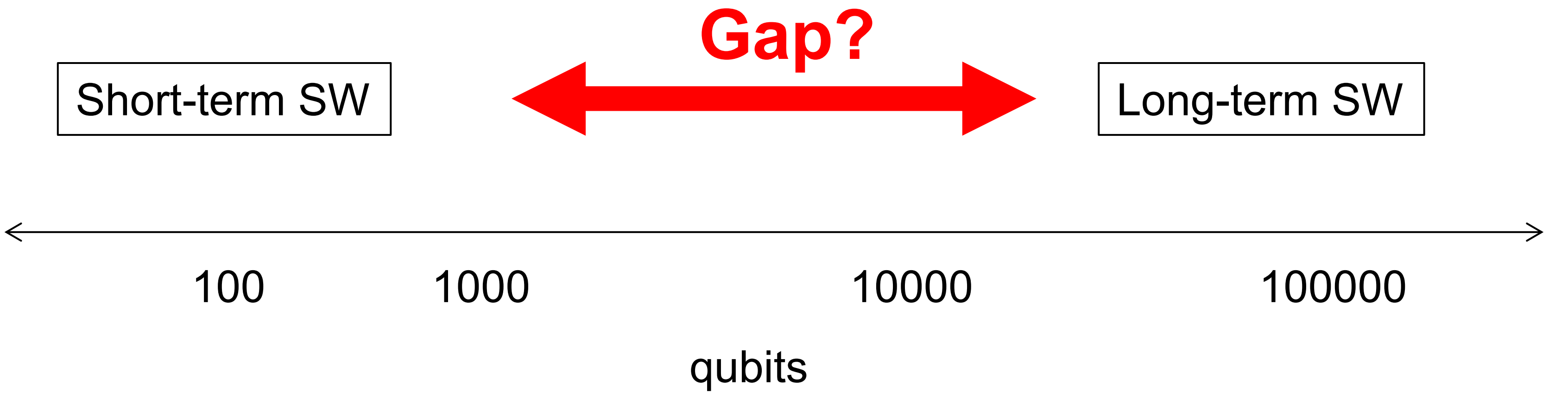
- Check implementation against a formal specification
- Check general quantum properties
  - No-cloning, entanglement, uncomputation
- Checks based on programmer assertions (quantum simulation)
- Heuristic bug-finding systems
  [Altadmri SIGCSE15]
- Can we check useful properties in polynomial time for programs with quantum supremacy?

What are the right abstractions?

- Specification Languages
  - Coq, Hamiltonians
- Programming Languages
  - Scaffold, Quipper, Q#, Quil …
- Instruction-Set Architectures
  - OpenQASM
- Physical Control
  - OpenPulse



Specialization vs Abstraction



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