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

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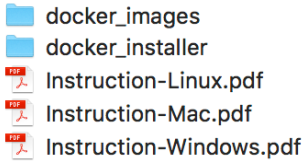
Tutorial Software Installation

- The USB drives with Docker tools and images are provided for you to complete the tutorial software installation.
- The instructions are in the USB drives.

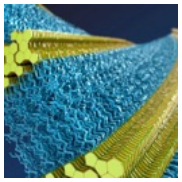


- After you run the *tutorial_starter* script, your web browser will open the jupyter notebook automatically.
- If the jupyter notebook doesn't run automatically, please copy/paste the URL, displayed in your terminal, to your web browser manually.
- Skip the step 4, "Edit IBM APIToken", in the instruction since we don't need to use IBM token for this tutorial.
- Disk space requirement: 12GB.

Raise your hand if you need any support.

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

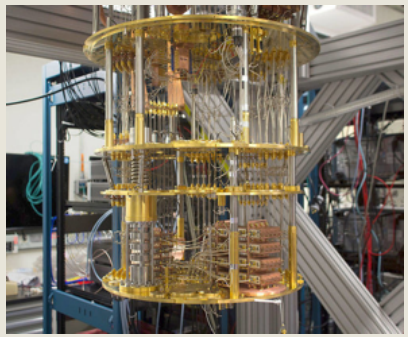


- A new industry and scaling curve to accelerate key applications
  - Not a full replacement for Moore's Law, but perhaps helps in key domains
- Lead to more insights in classical computing
  - Previous insights in chemistry, physics and cryptography
  - Challenge classical algorithms to compete w/ quantum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

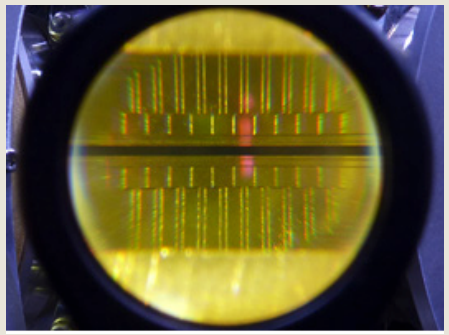
NISQ

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).

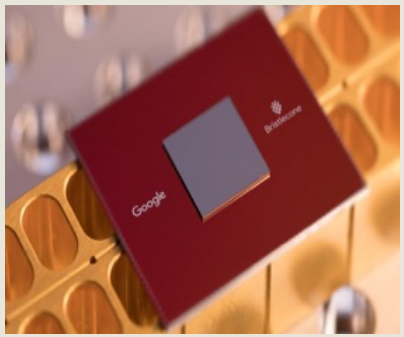
– John Preskill, Caltech



IBM
50 superconductor qubits

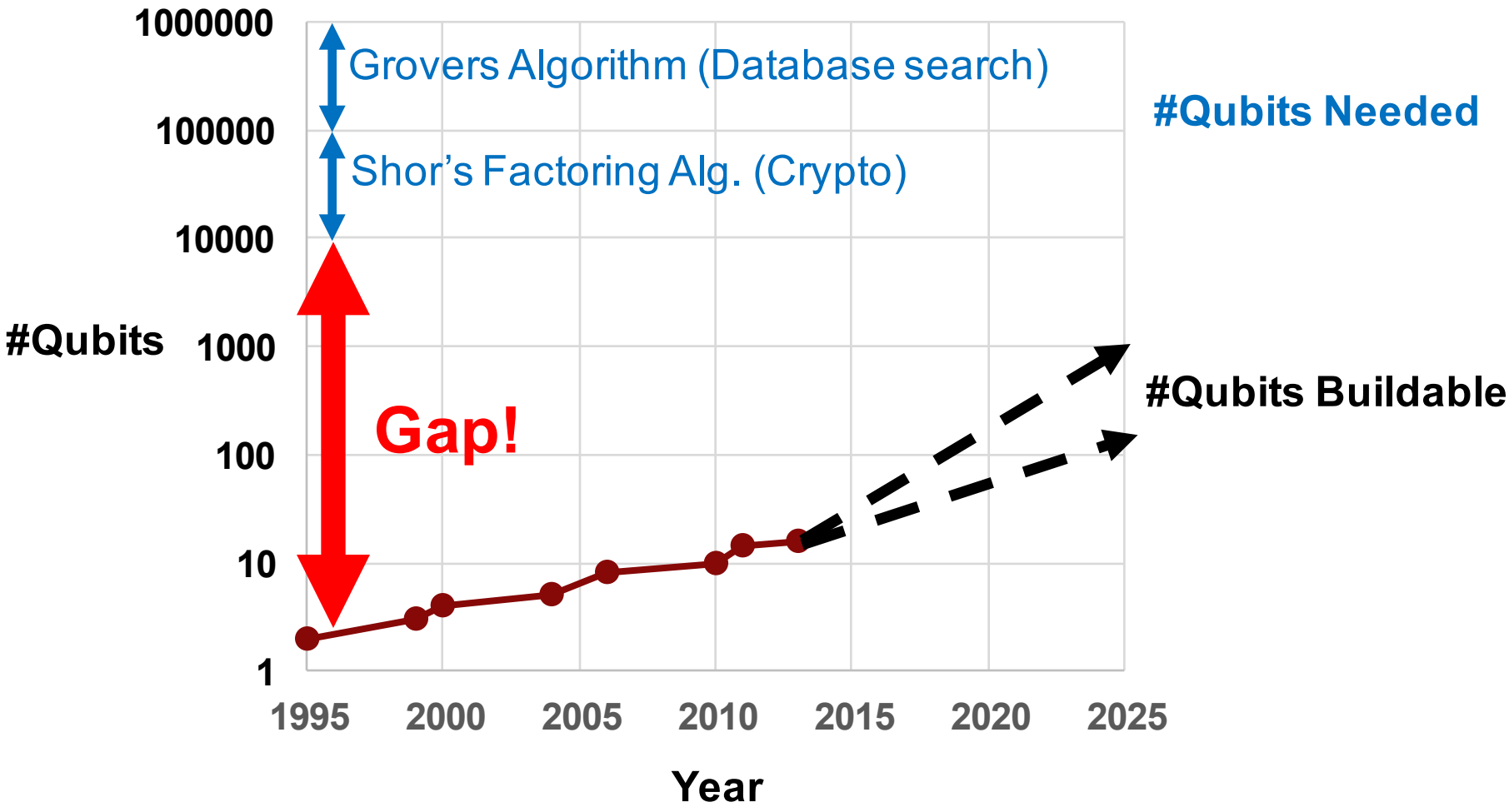


Innsbruck
20 atomic ion qubits

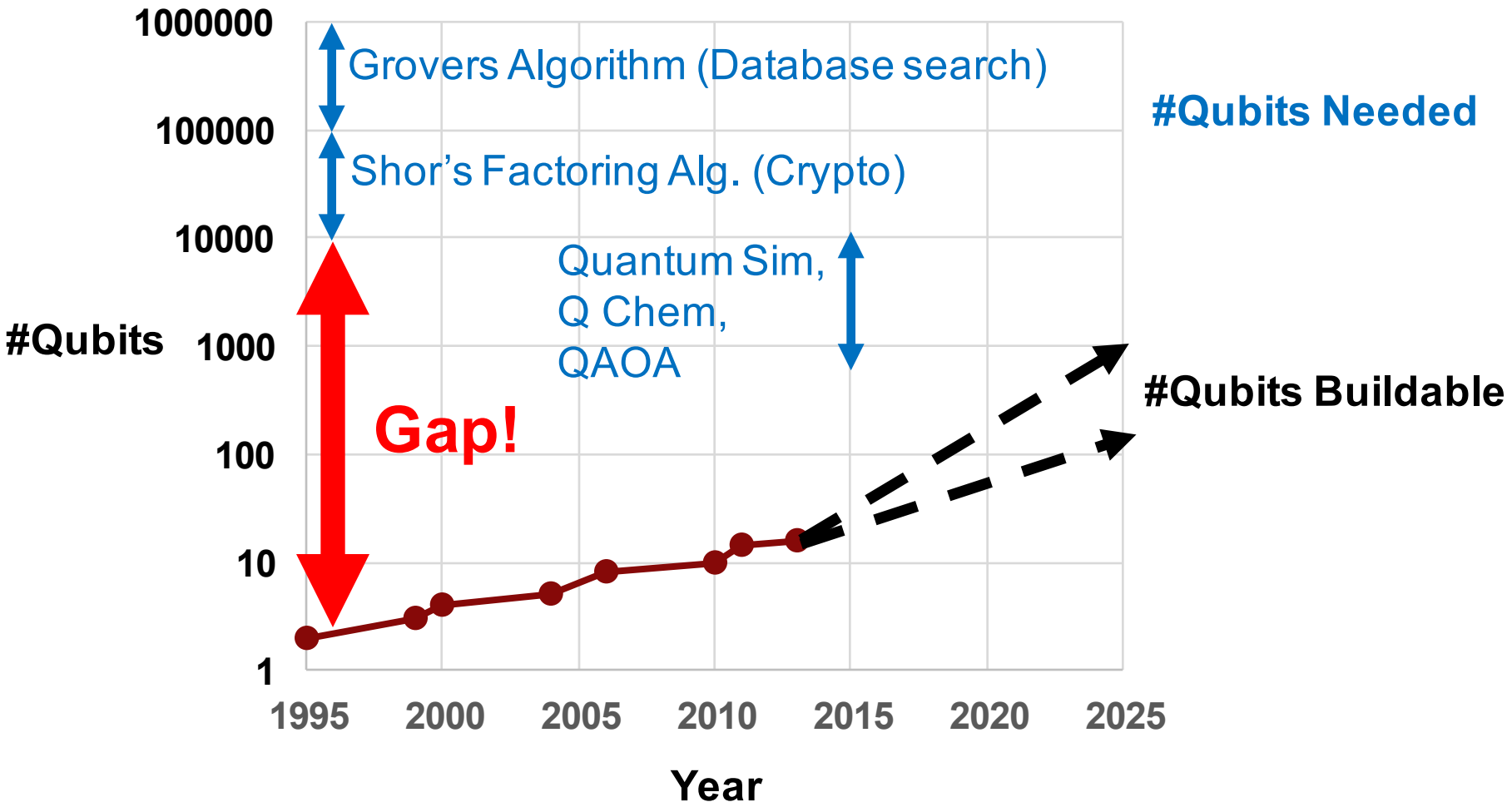


Google
72 supercond qubits

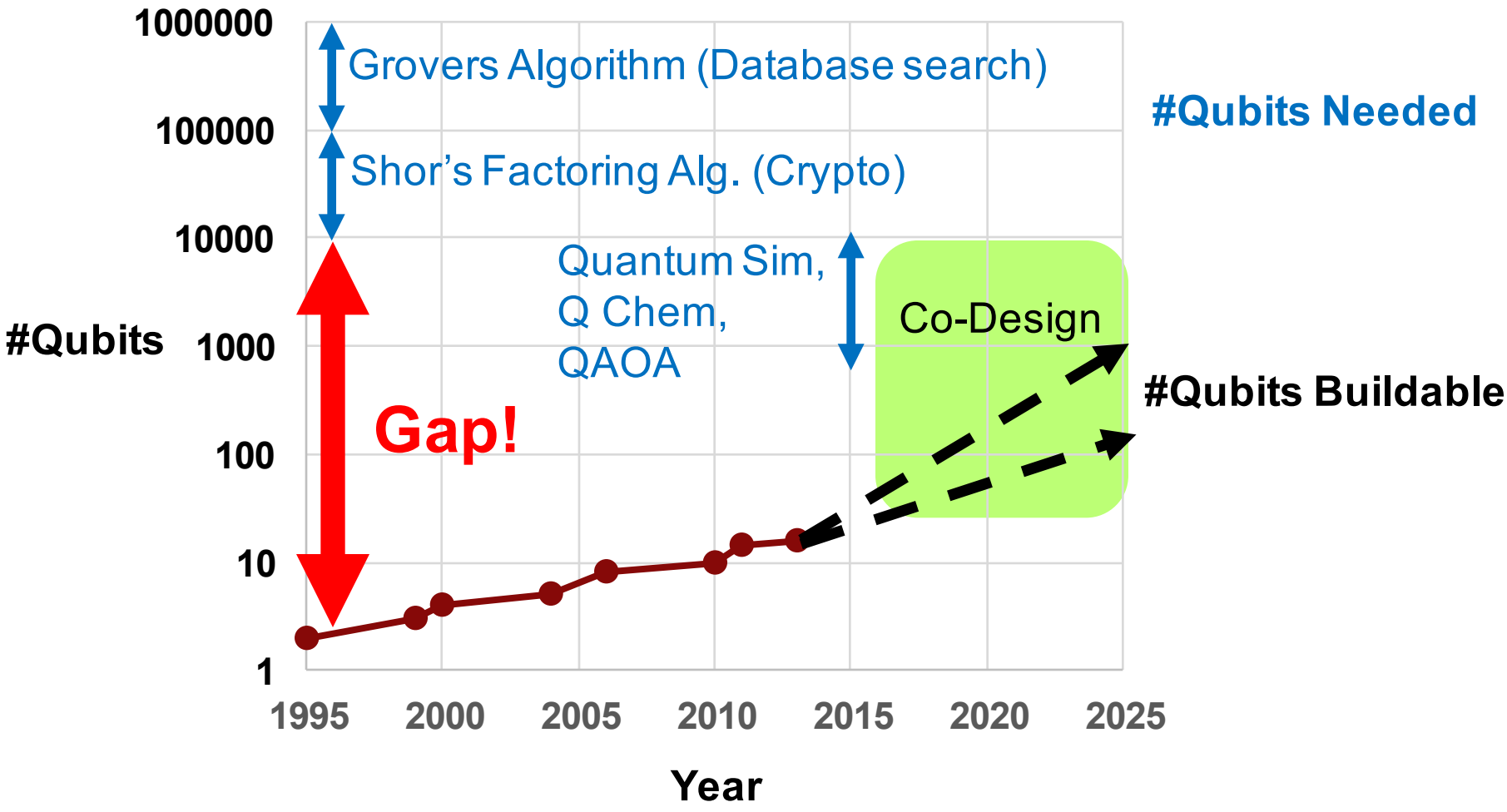
The Algorithms to Machines Gap



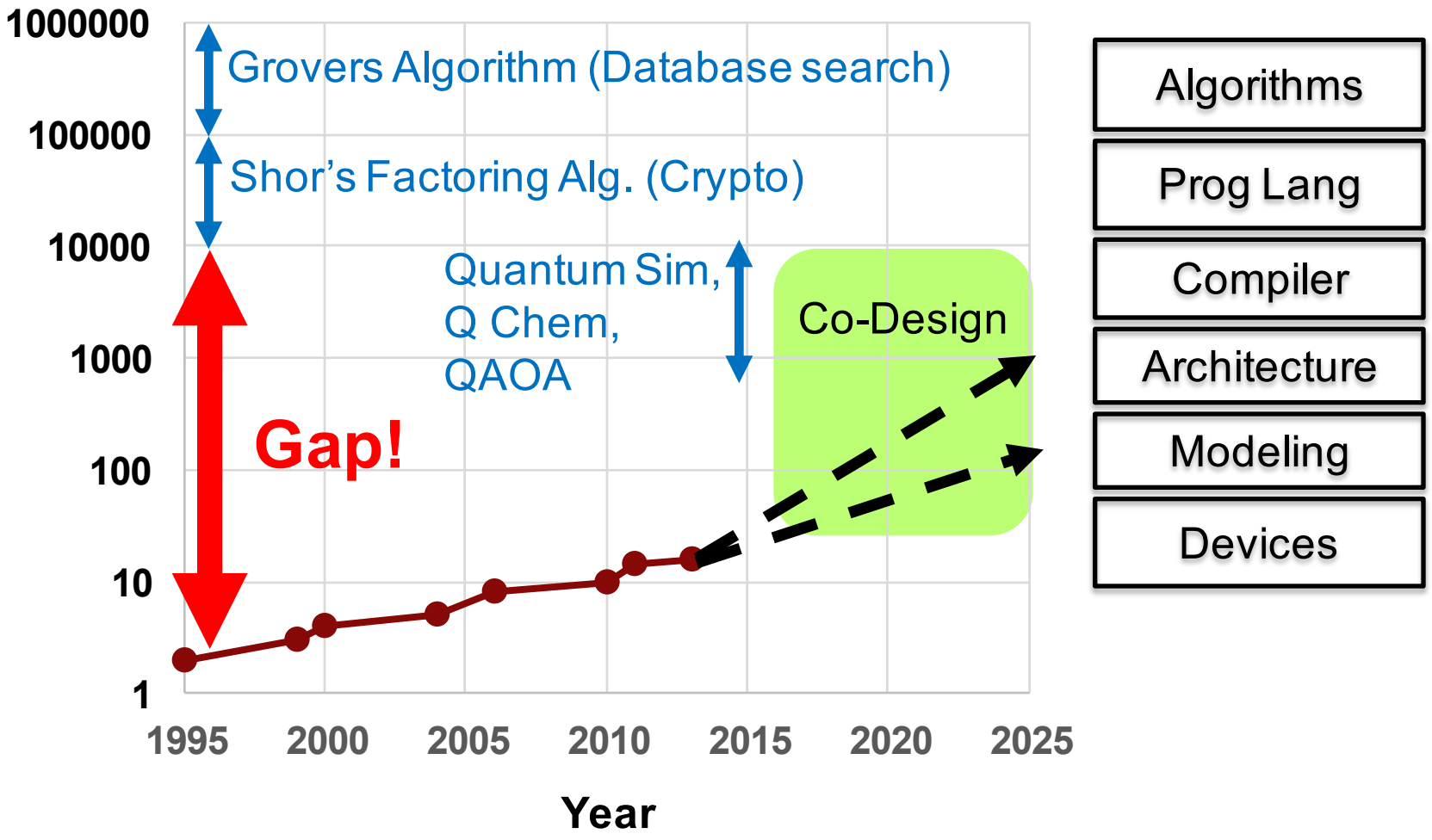
The Algorithms to Machines Gap



The Algorithms to Machines Gap

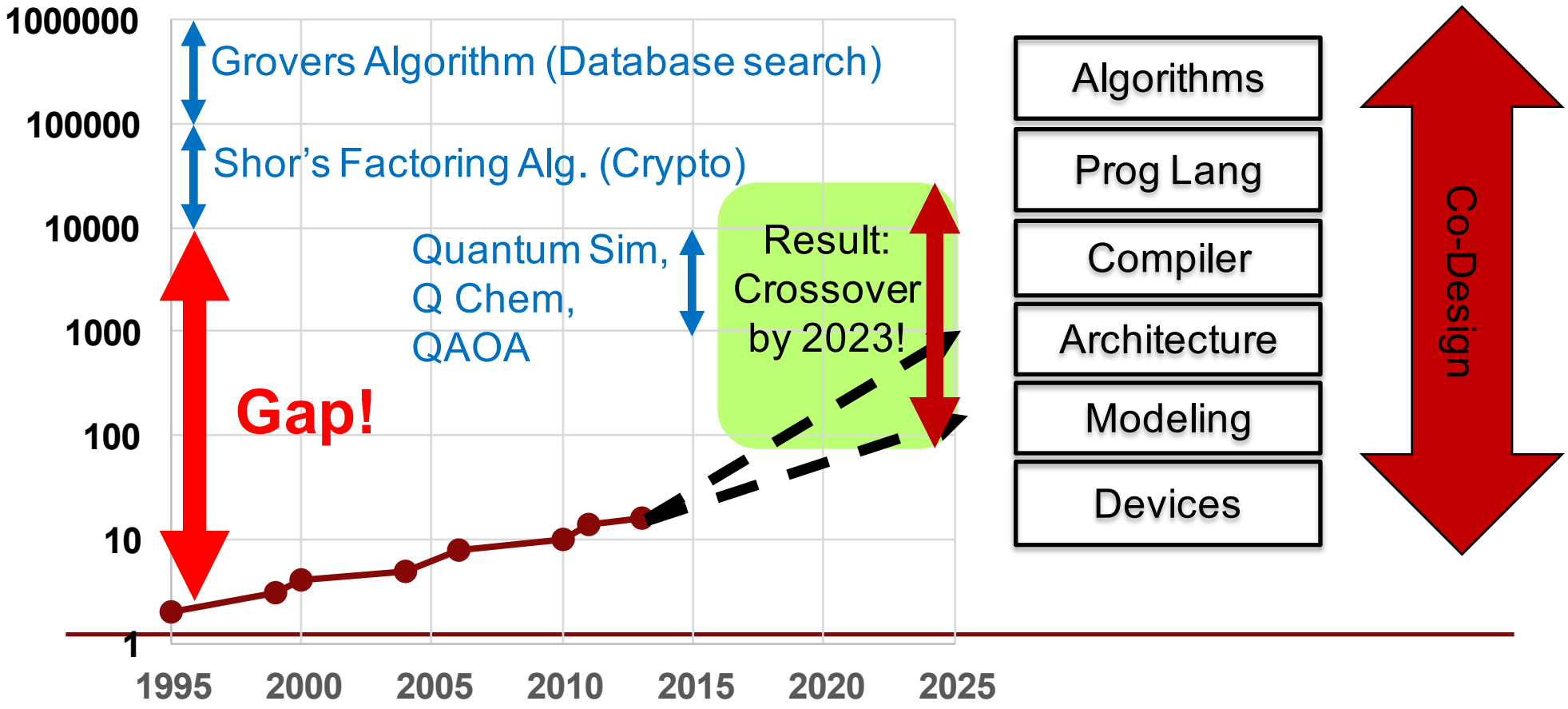


Closing the Gap: Software-Enabled Vertical Integration and Co-Design

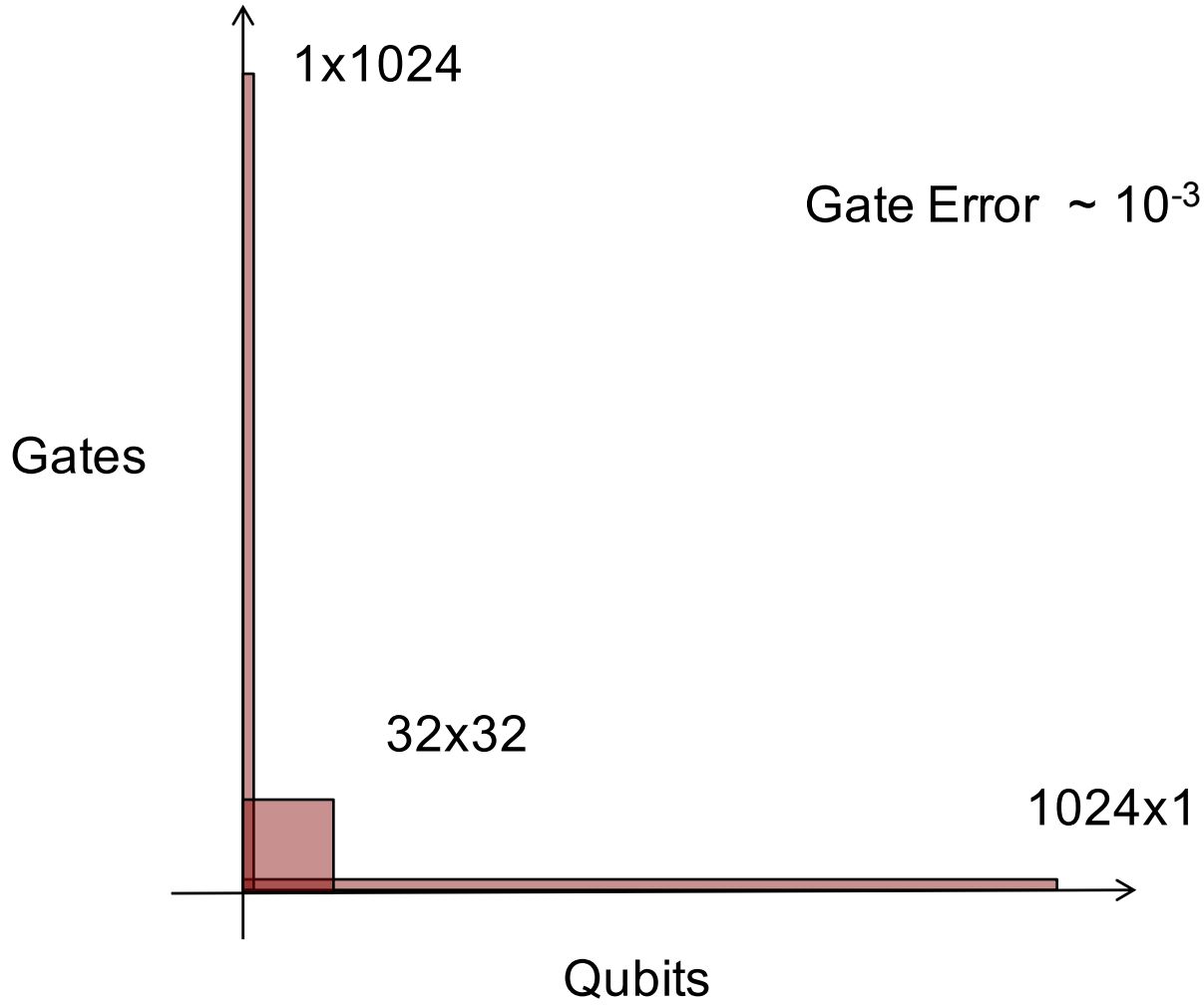


Goal

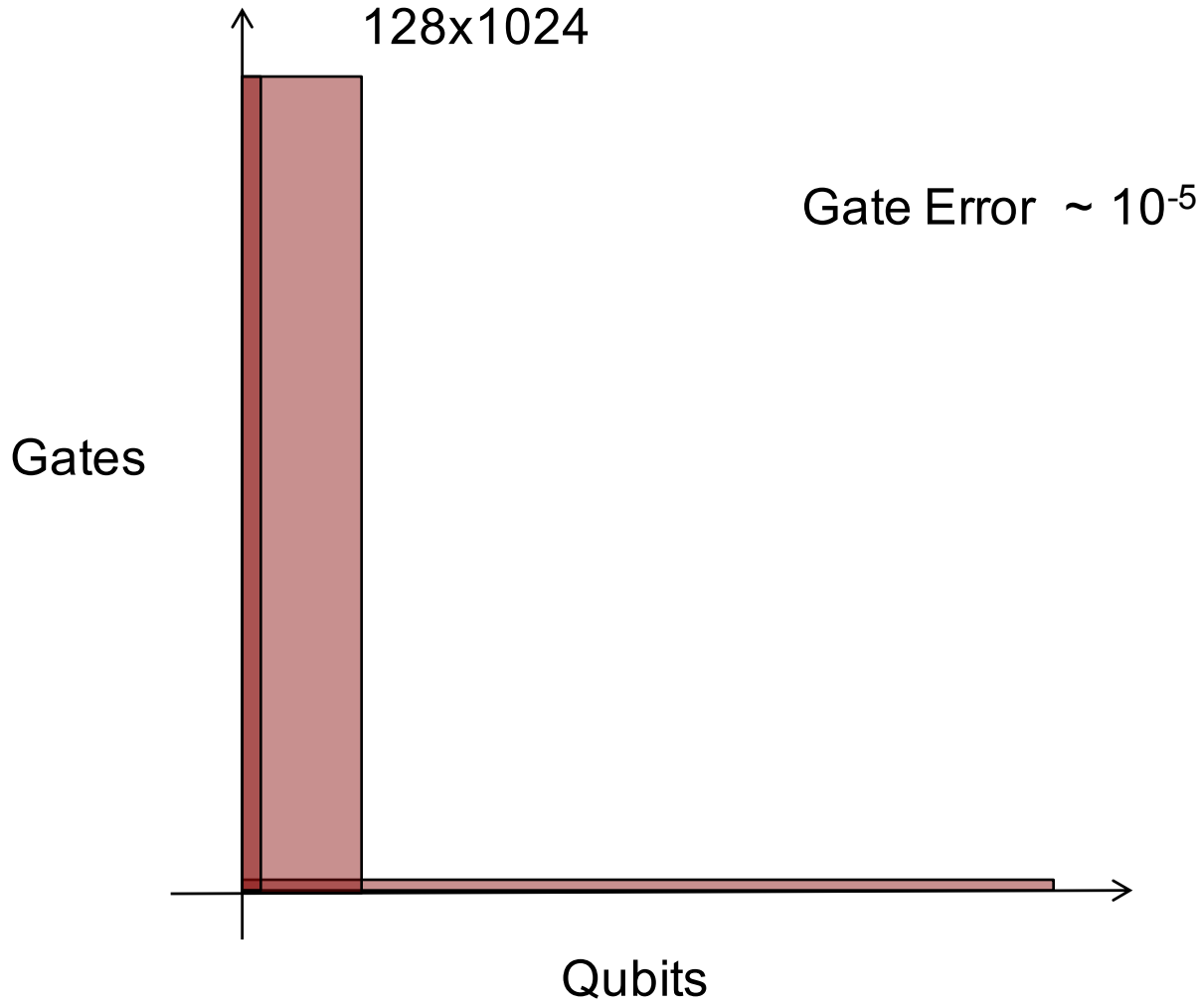
Develop co-designed algorithms, SW, and HW to close the gap between algorithms and devices by 100-1000X, accelerating QC by 10-20 years.



Space-Time Product Limits



Space-Time Product Limits



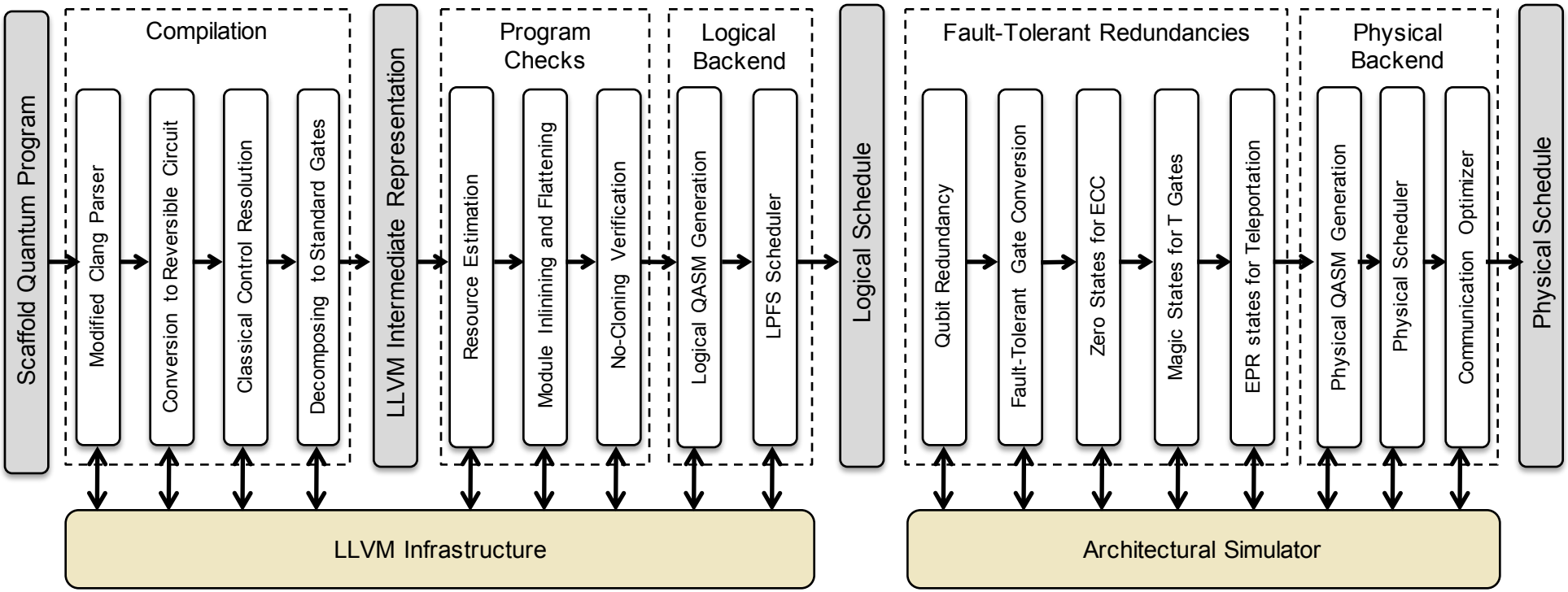
“Good” Quantum Applications

- 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



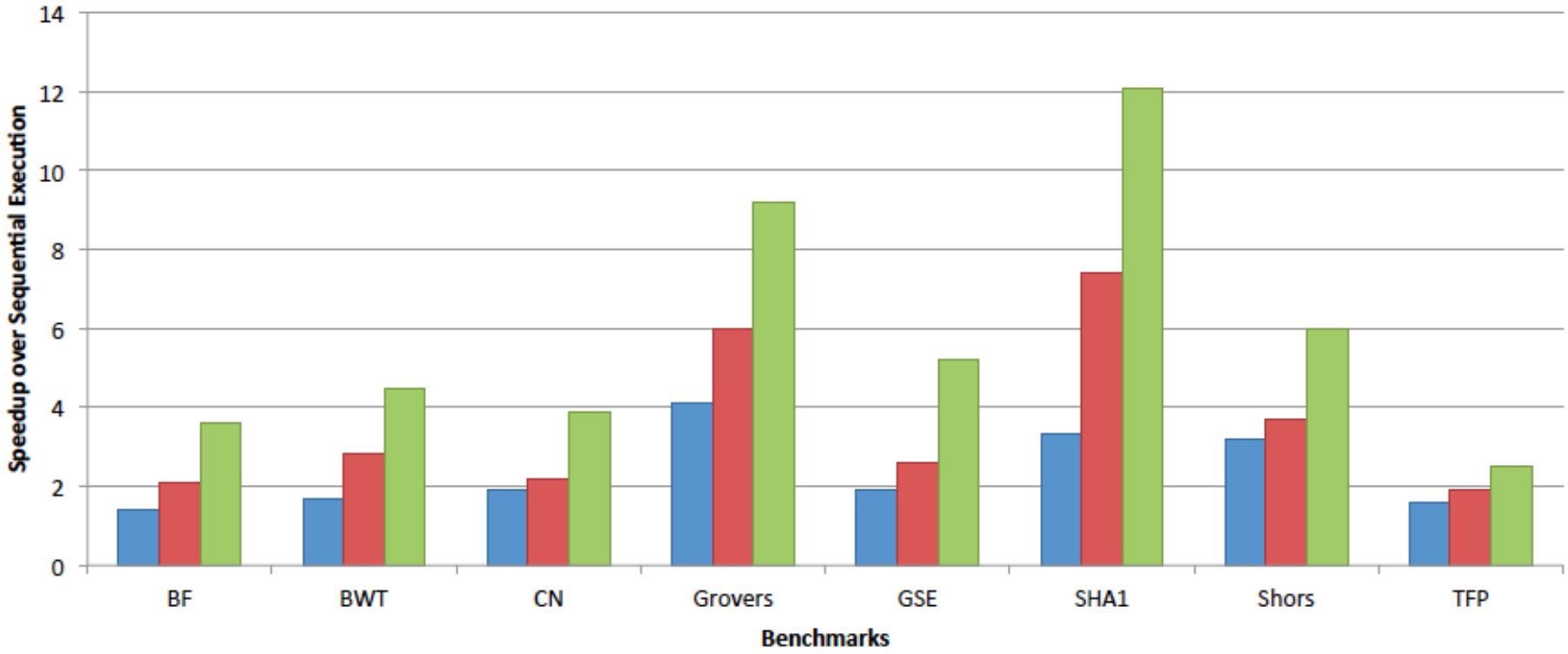
Scaffold tools, 41K lines of code, open source
epiqc.cs.uchicago.edu

https://github.com/epiqc/ScaffCC

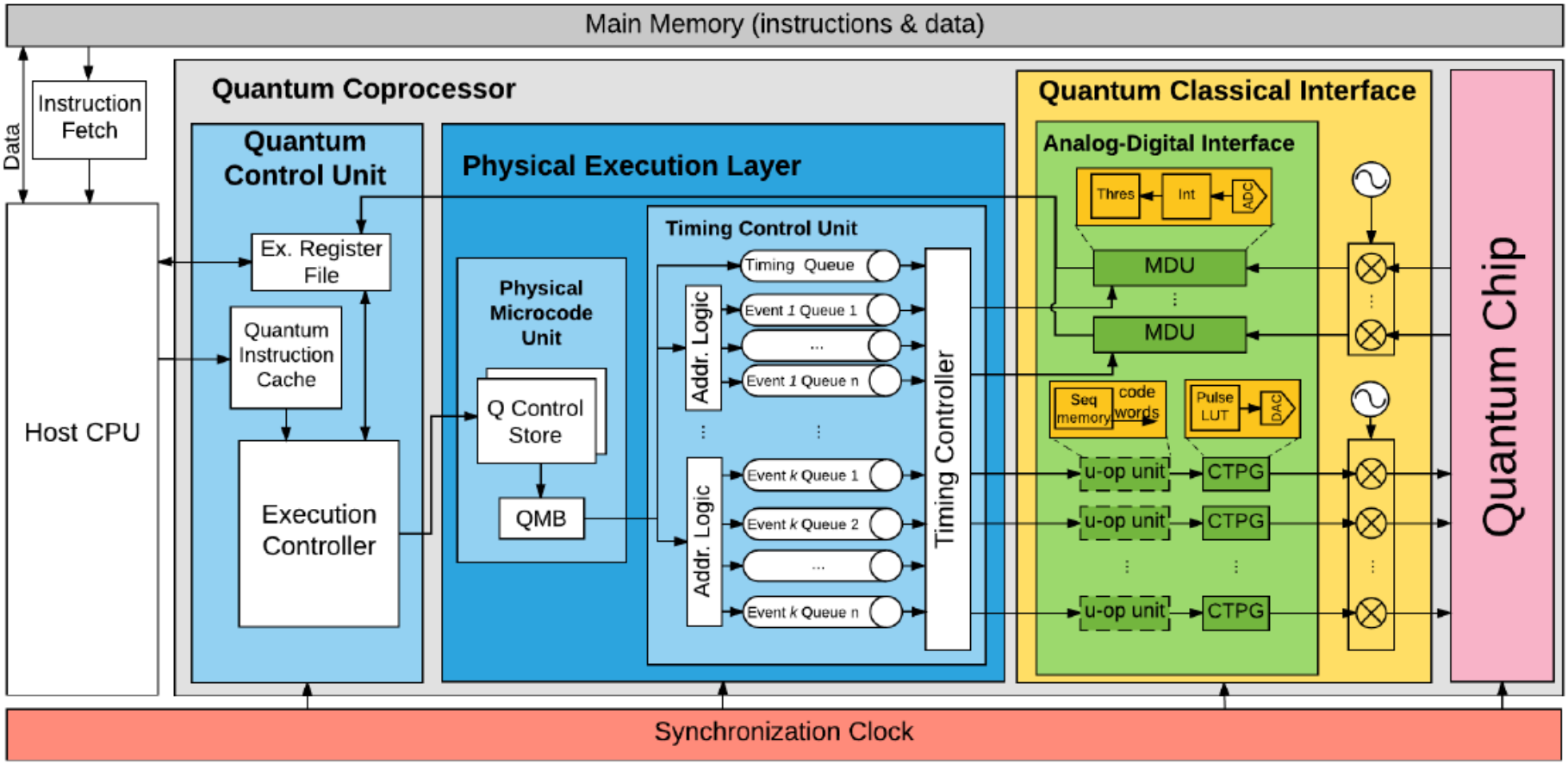
Increasing Parallelism

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

[Heckey+ ASPLOS 2015]

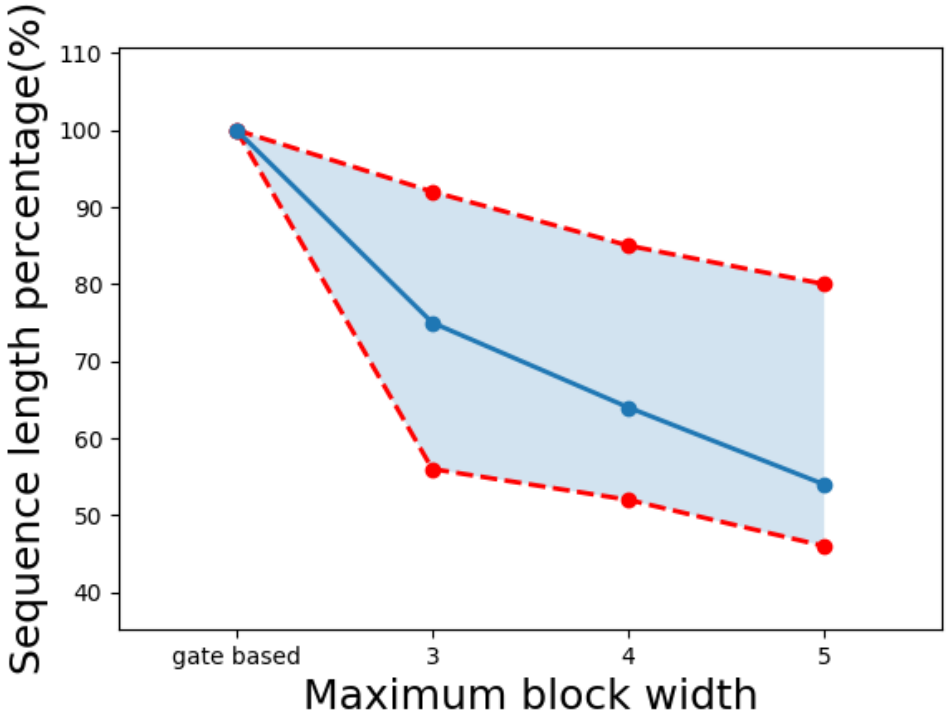


Microarchitecture



[Fu+ Micro 2017 Best Paper]

Breaking ISA Abstraction

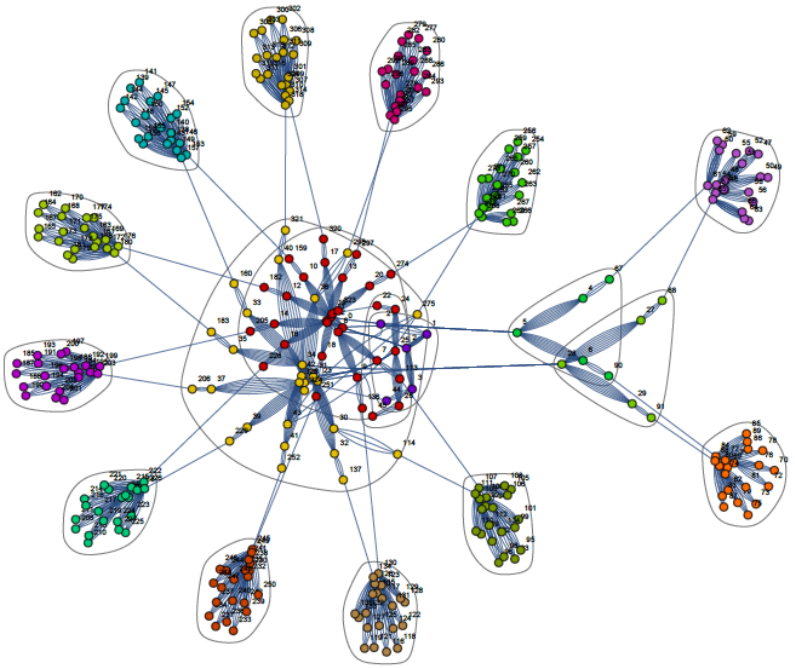


- Multi-Qubit Operators for QAOA
  - Direct translation from compiler to control pulses

[Joint work with David Schuster]

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

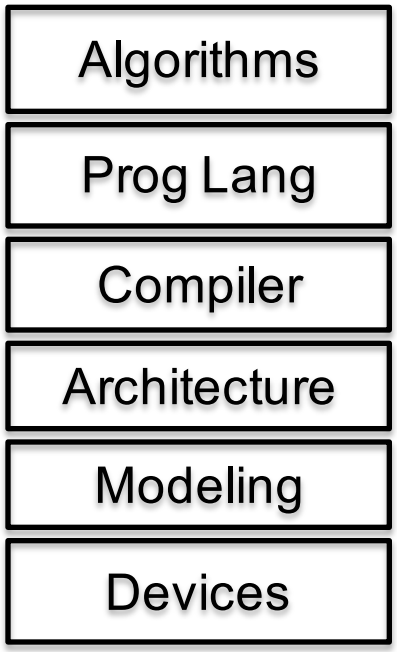
How do I know if my QC program is correct?

- 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