Leading the evolution of compute: Quantum Computing

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HPC User Forum April 18, 2018

Quantum Computing: Key Concepts

Superposition

Classical Physics

Heads or Tails

Quantum Physics

Heads and Tails

Entanglement

1) 

2) 

3) 

4) 

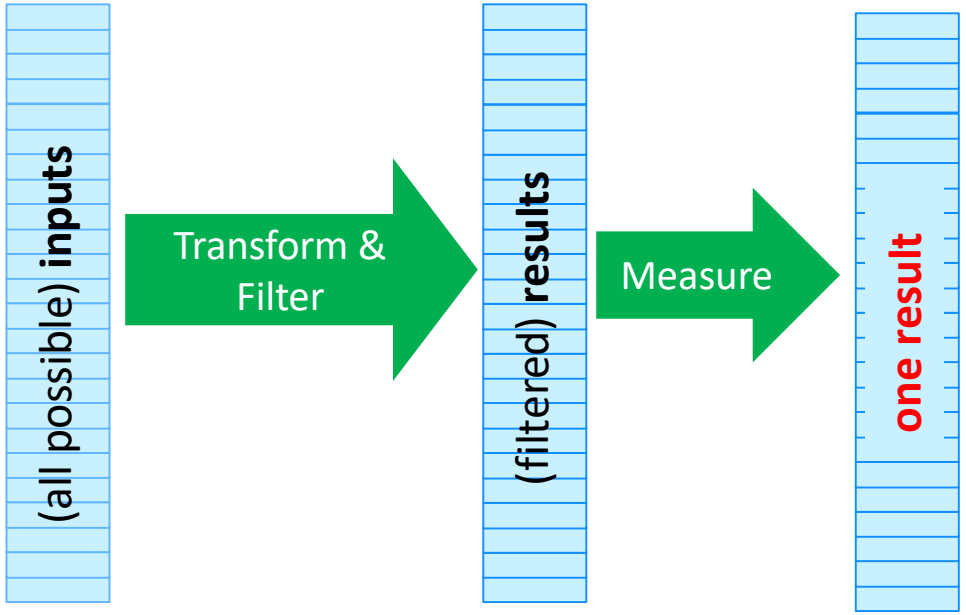
N Quantum Bits or **Qubits =** 2^N States

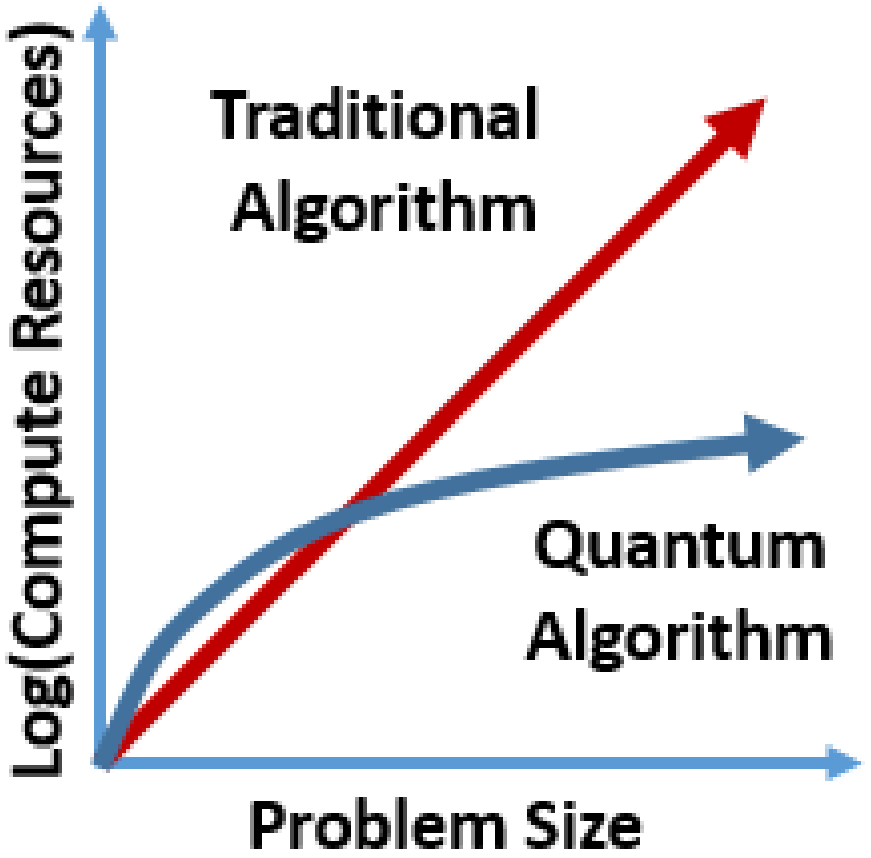
- 50 Entangled Qubits = more states than any possible supercomputer
- 300 Entangled Qubits = more states than atoms in the universe
- Fragility will require error correction and likely millions of qubits

Fragility

Observation or noise causes loss of information

The promise of quantum computing



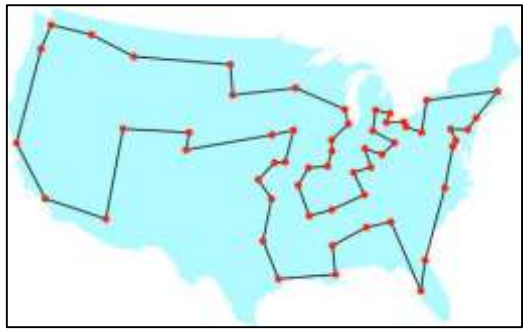


Exponential speedup ←→ surpassing the limits of scaling

Changing the World

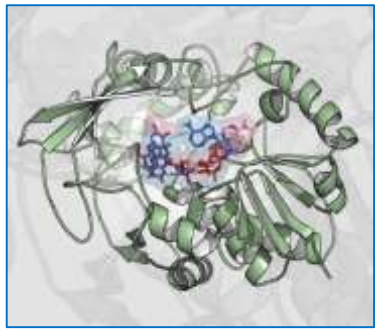
TIME

“Quantum Will Change Everything”

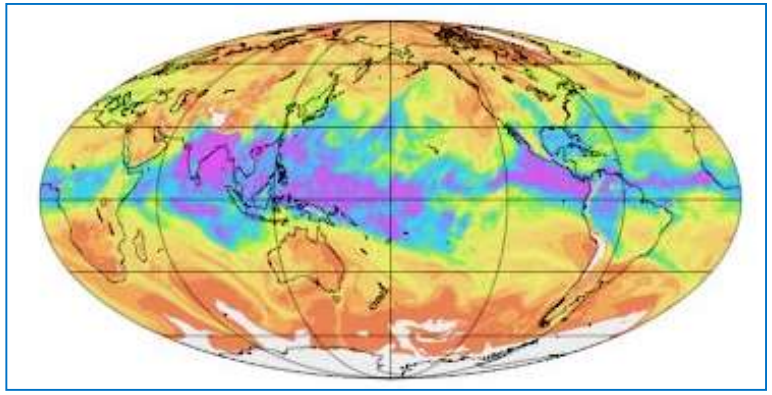


Travel and Logistics

Image Processing



Pharmacology



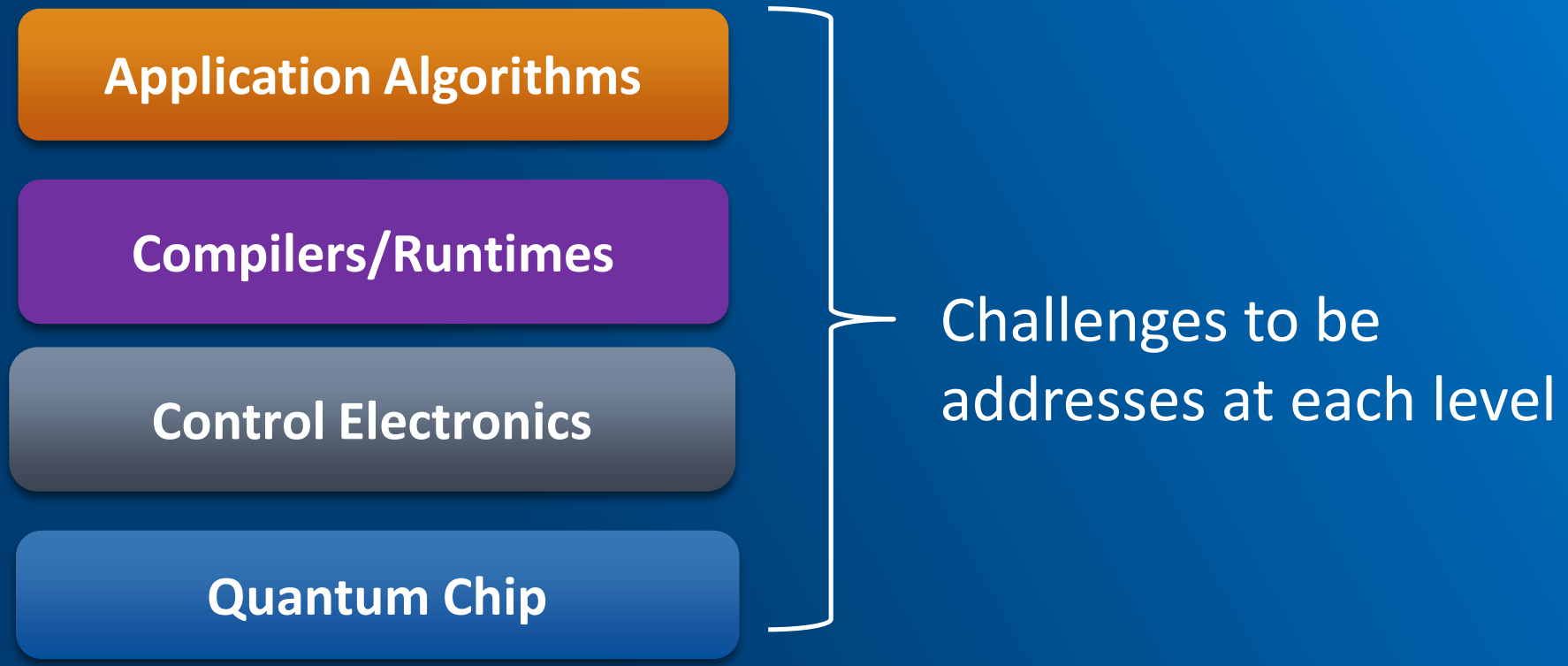
Improved Forecasting

Improved Stock ROI

Cryptography

Source: Google Images

Developing a Quantum Computer System



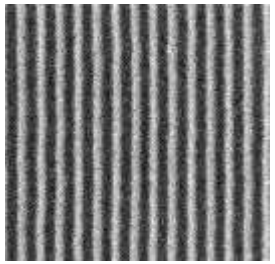
Intel – QuTech Research Collaboration

Intel Labs:

- Algorithms
- System Architecture
- Control Electronics

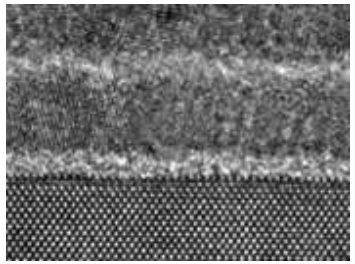
TMG Components Research

Patterning



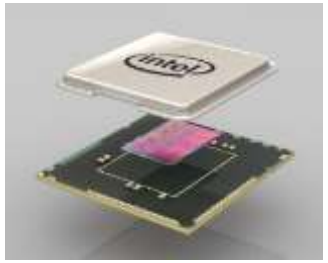
24nm Pitch Lines

Atomic Layer Control



Metal Gate / High k on 300mm Silicon Wafer

Packaging

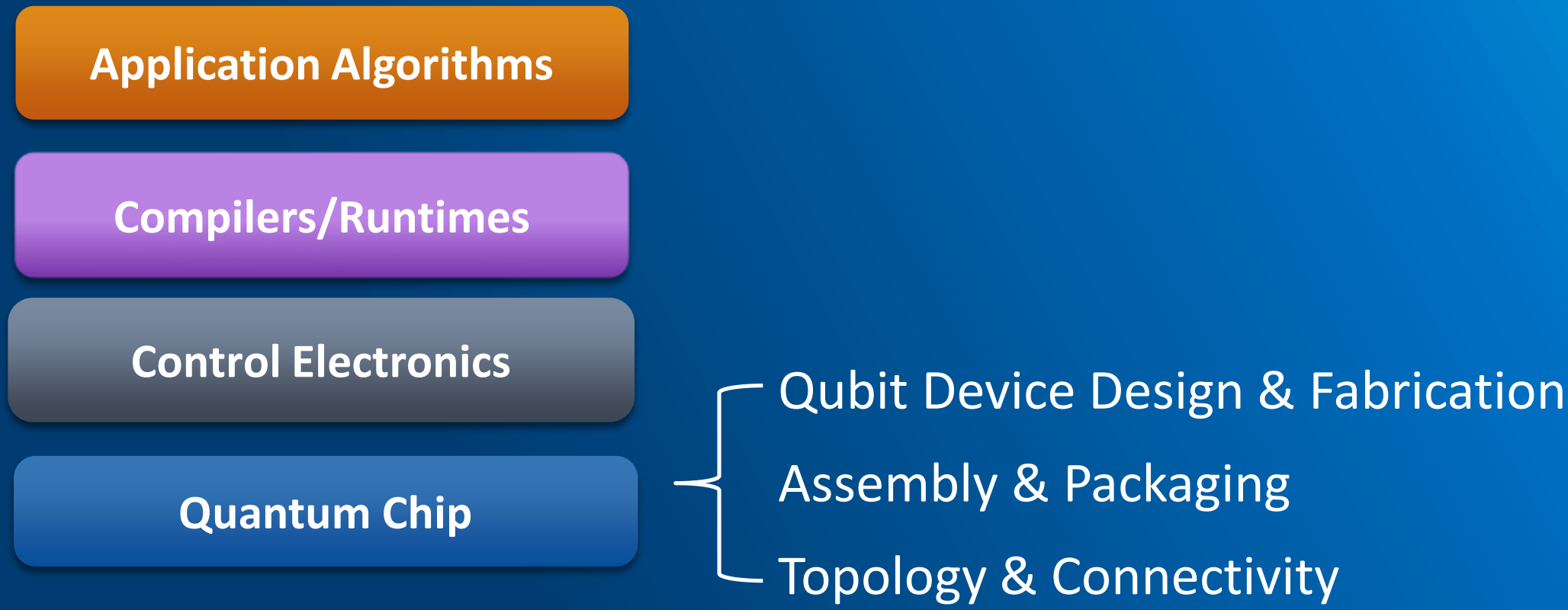


Assembly and Packaging Research

QuTech's Expertise in qubit operation and control

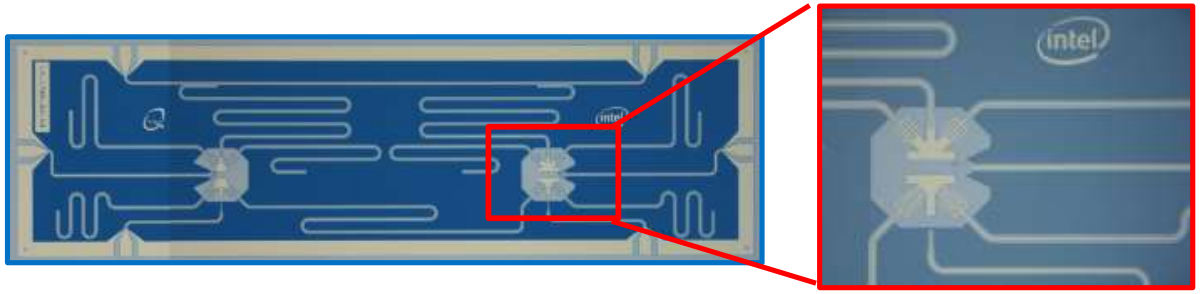
Combining Intel capabilities with Delft expertise

Developing a Quantum Computer System

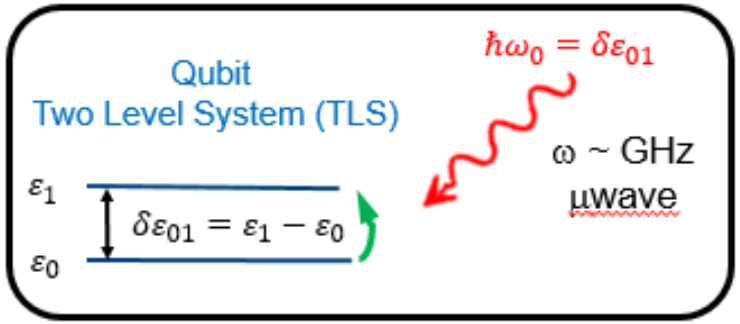


Building Better Qubits

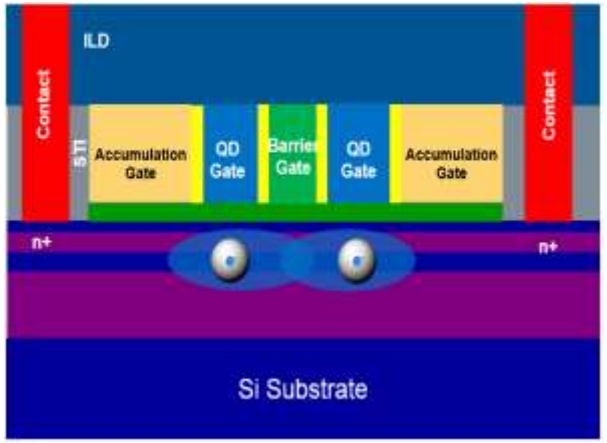
Superconducting Qubits

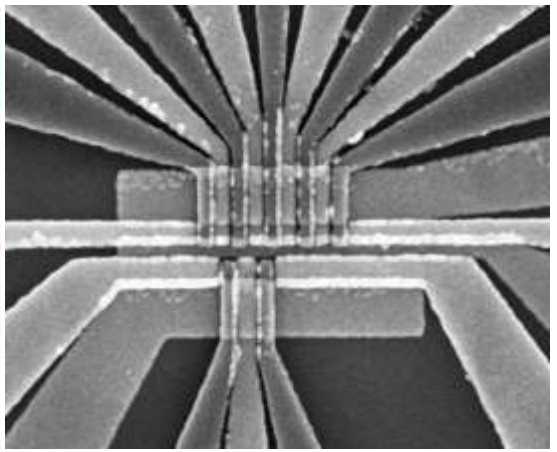


Very high quality microwave circuit

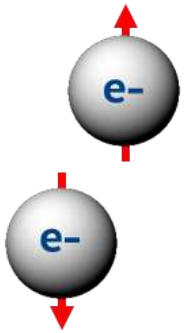


Spin Qubits in Silicon





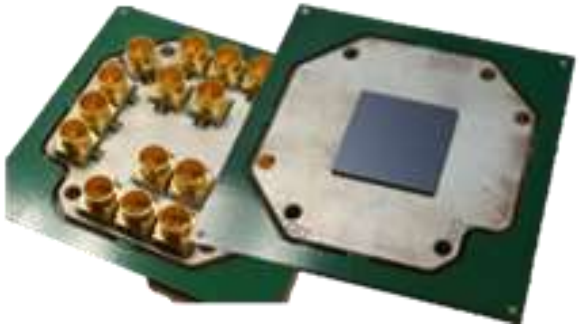
Single electron transistors, where qubit is spin state



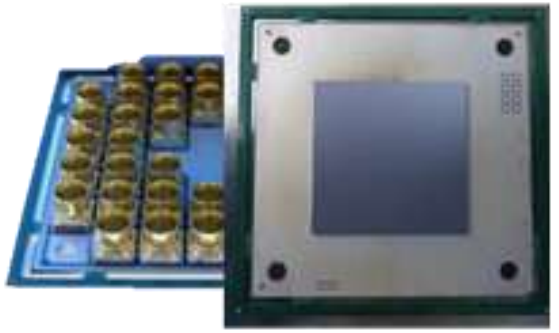
Superconducting Qubit Progress

Resonator

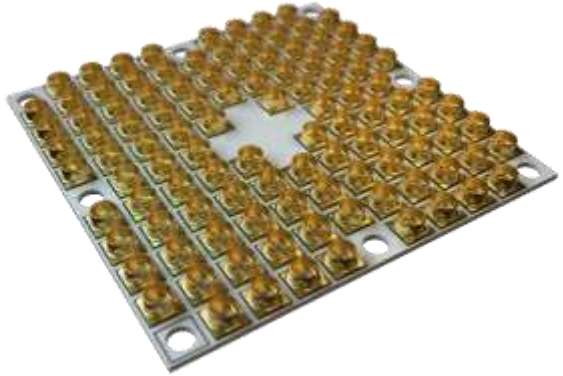
6 Qubits



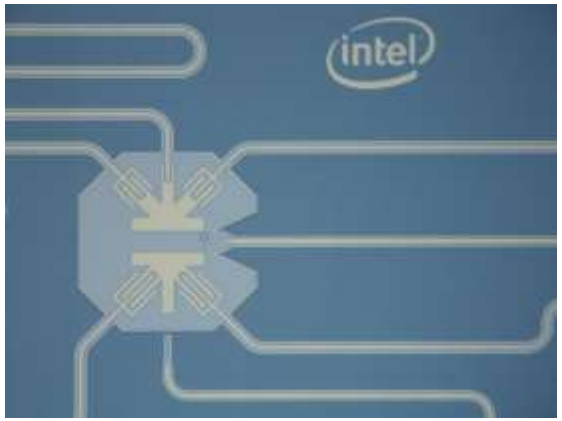
7 Qubit Array



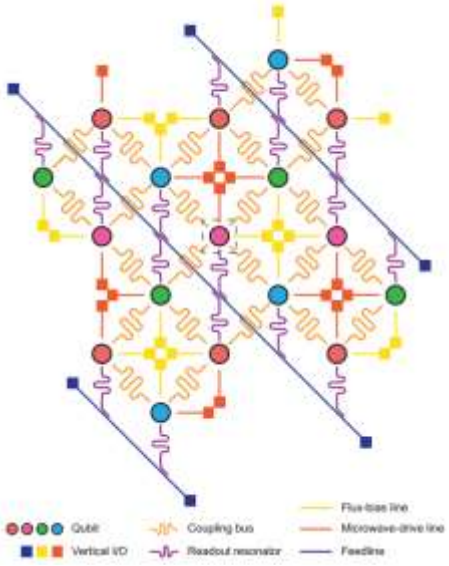
17 Qubit Array



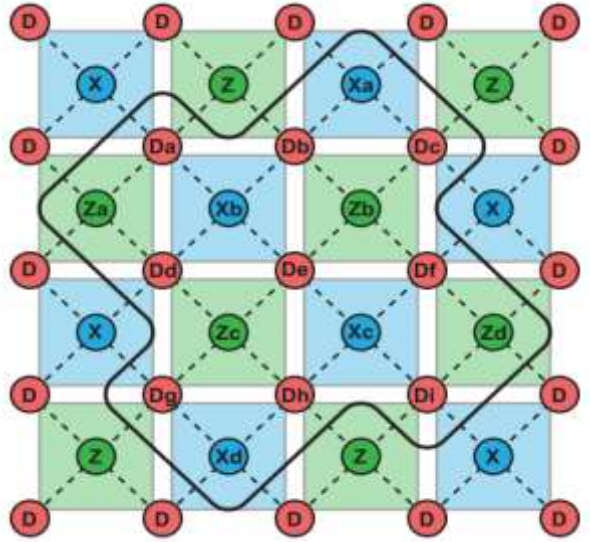
Tangle Lake



Starmon Geometry
with up to 30us T1



Shared Feedlines



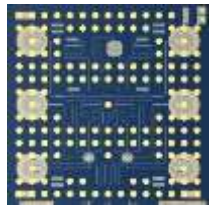
Surface Code Topology

Flip-chip die evolution

Octobox

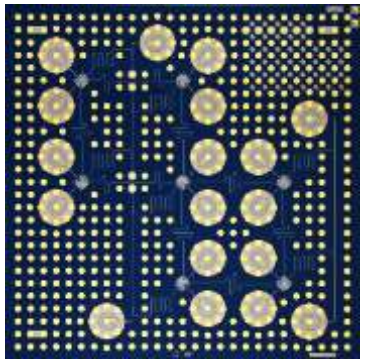
2mm x 7mm

6-port FC



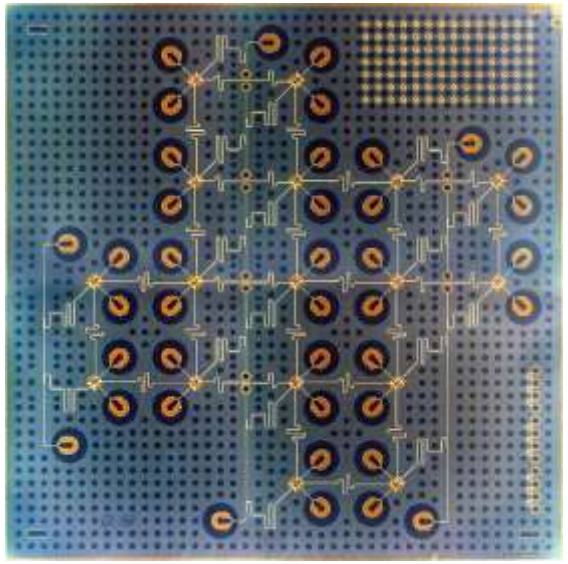
8mm x 8mm

Surf-7 FC



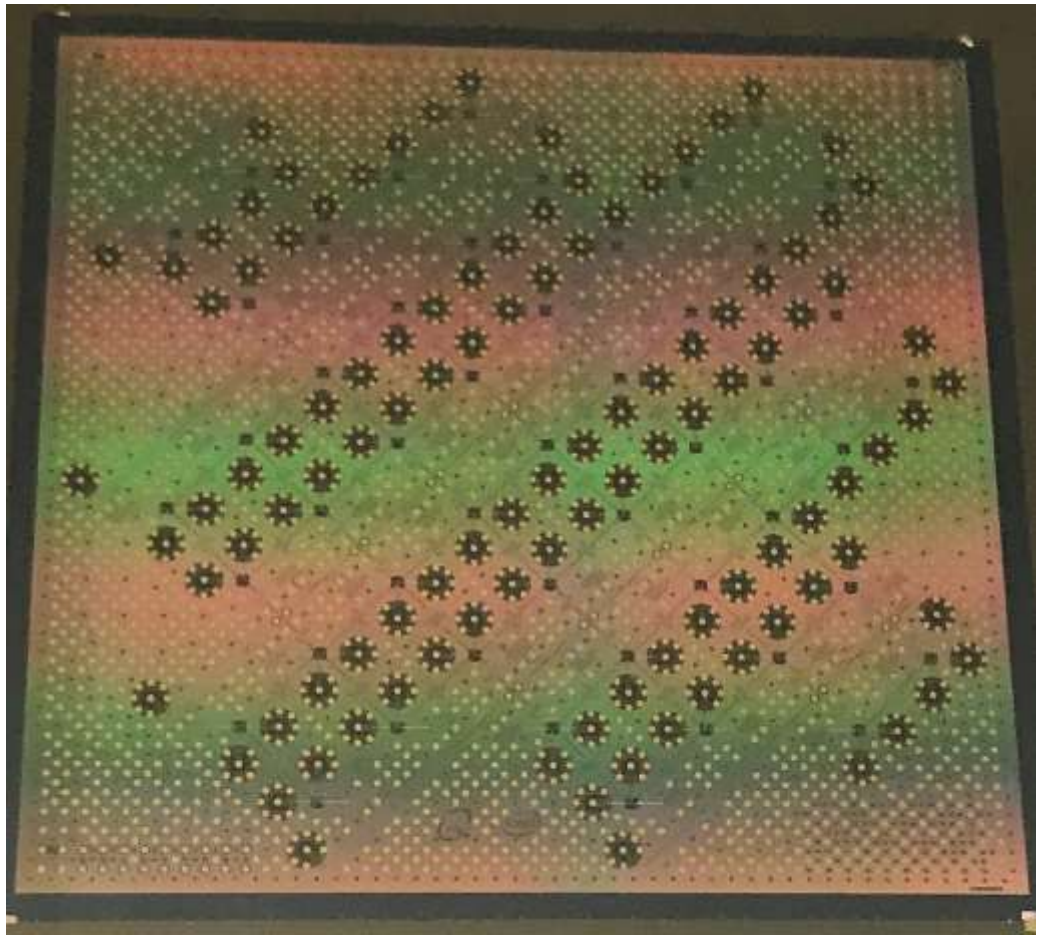
14mm x 14mm

Surf-17 FC



22mm x 22mm

Surf-49 FC



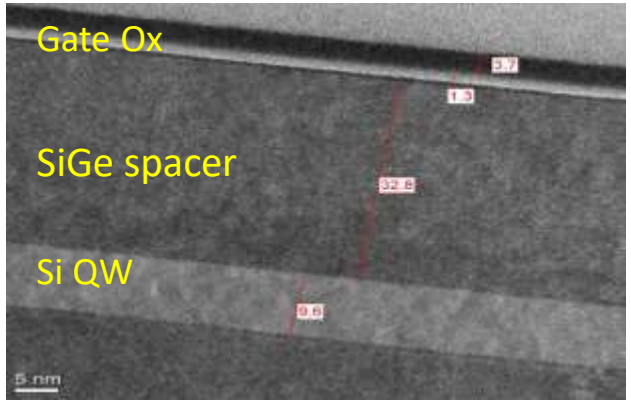
36mm x 36mm

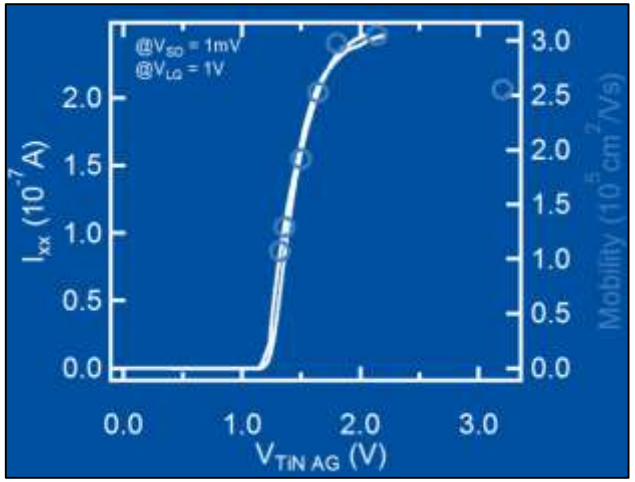
wire bonding around perimeter

Flip-chip bonding

TSVs needed

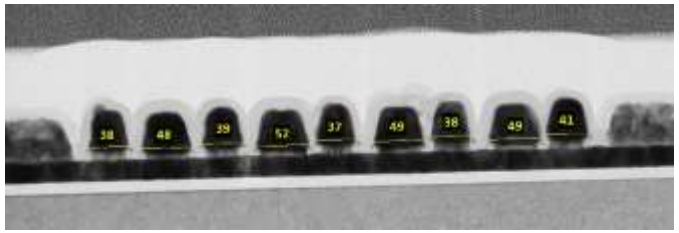
Spin Qubits In Silicon

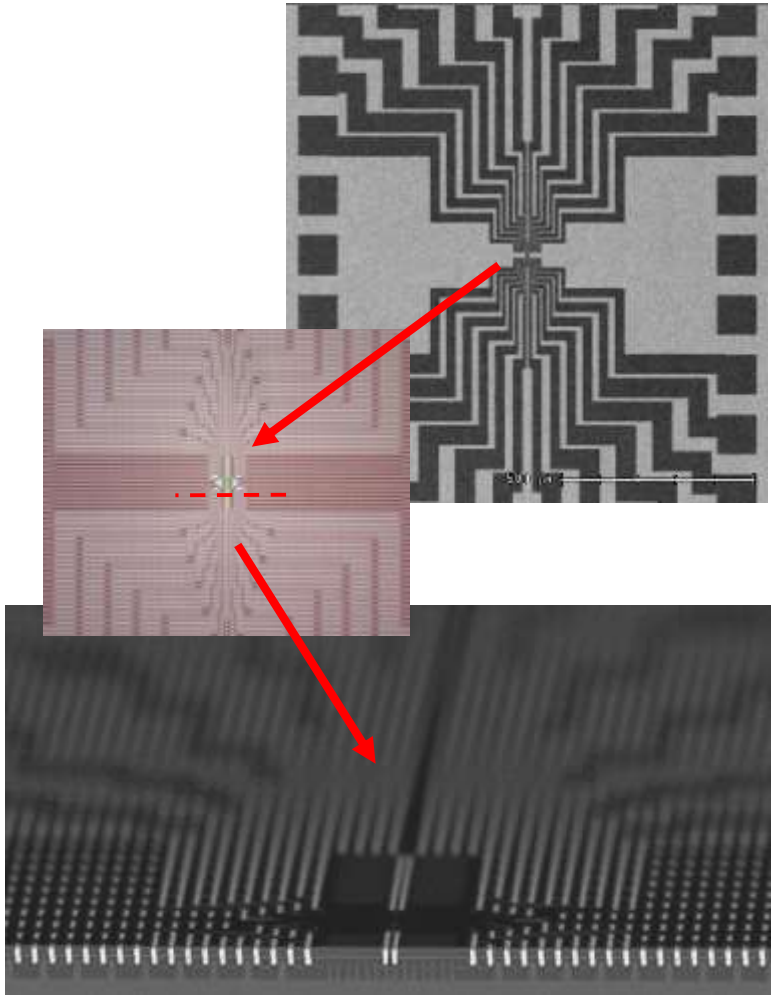




First 300mm isotopically pure silicon and world class mobility

Characterizing LAB devices





QD array devices almost ready with FAB quality Si

Spin Qubits at higher temperatures

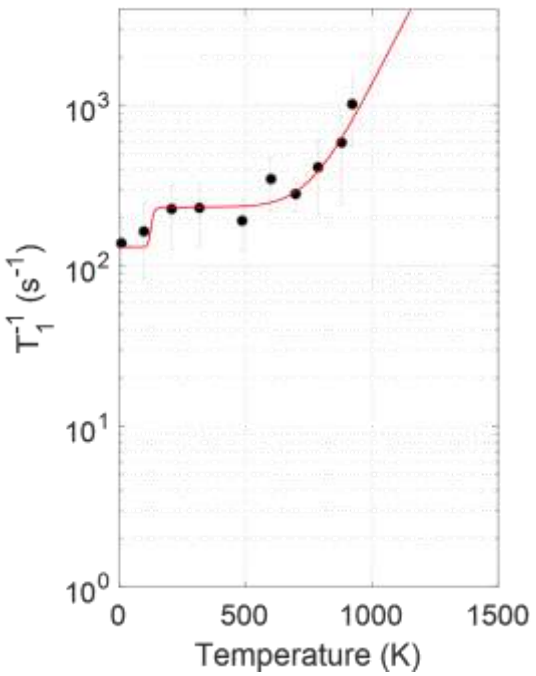
Hot-Qubits

- To increase cooling power available for larger arrays

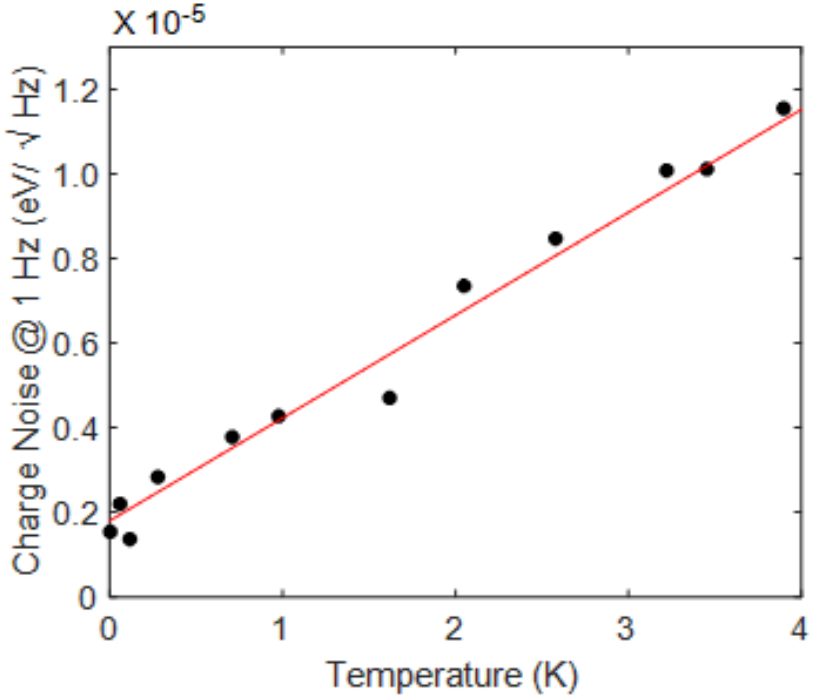
- Spin Relaxation
  - Short coherence times affects gate operations
  - ➢ T_1=2.8ms @ 1.1K; longer at lower B / higher Evs

- Charge Noise
  - Single qubit gates & two-qubit gates are affected
  - ➢ Linear increase 1 – 4K

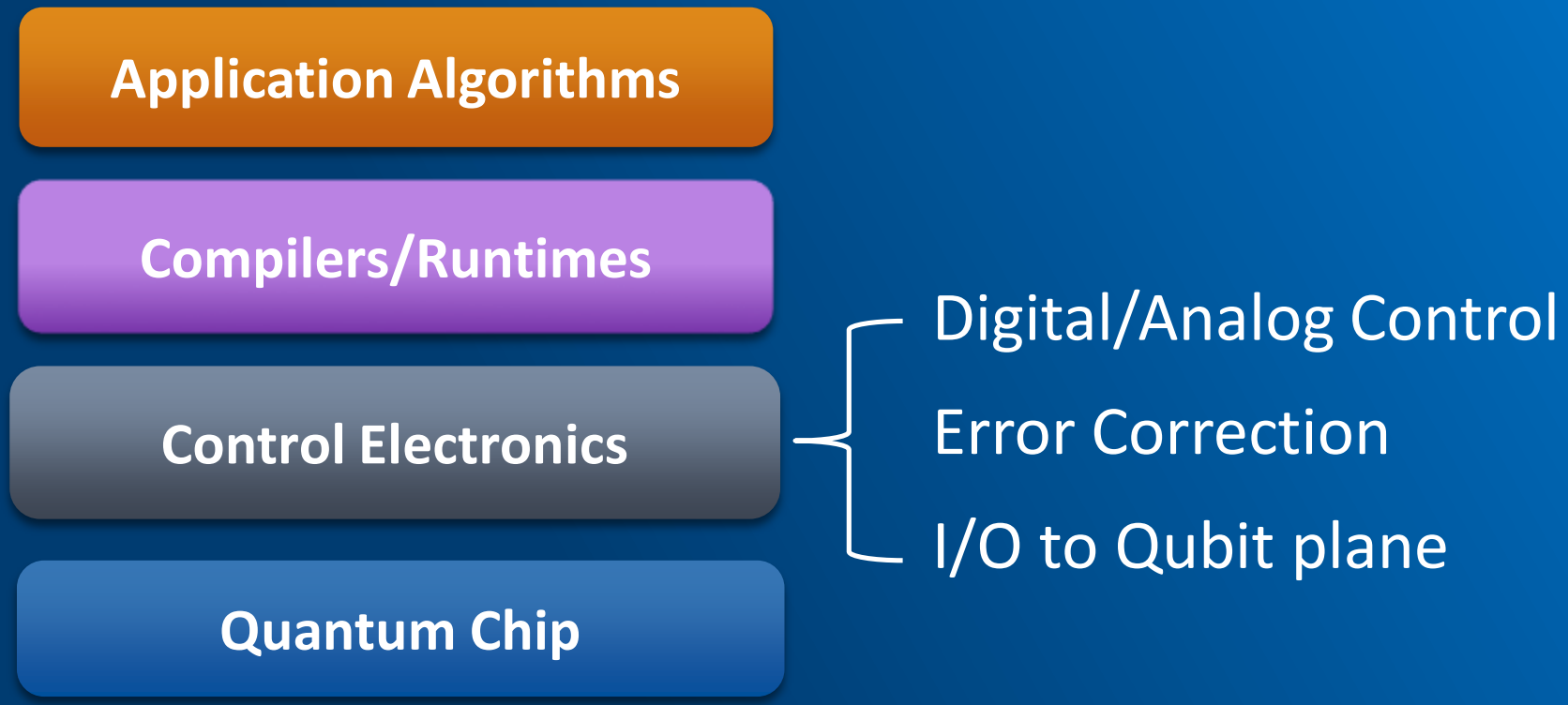
Relaxation time T_1



Charge Noise



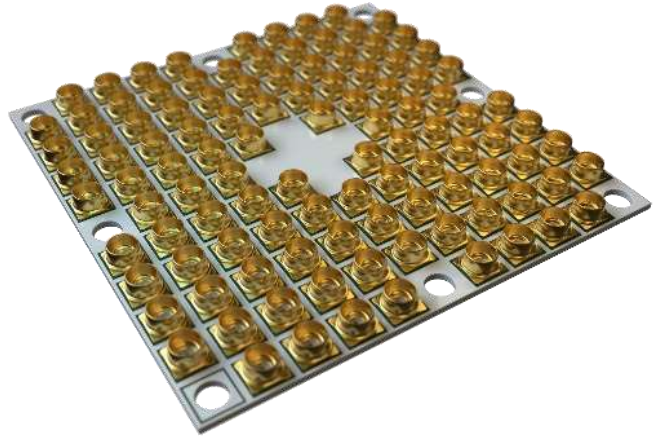
Developing a Quantum Computer System



Scaling I/O to the Qubit Plane

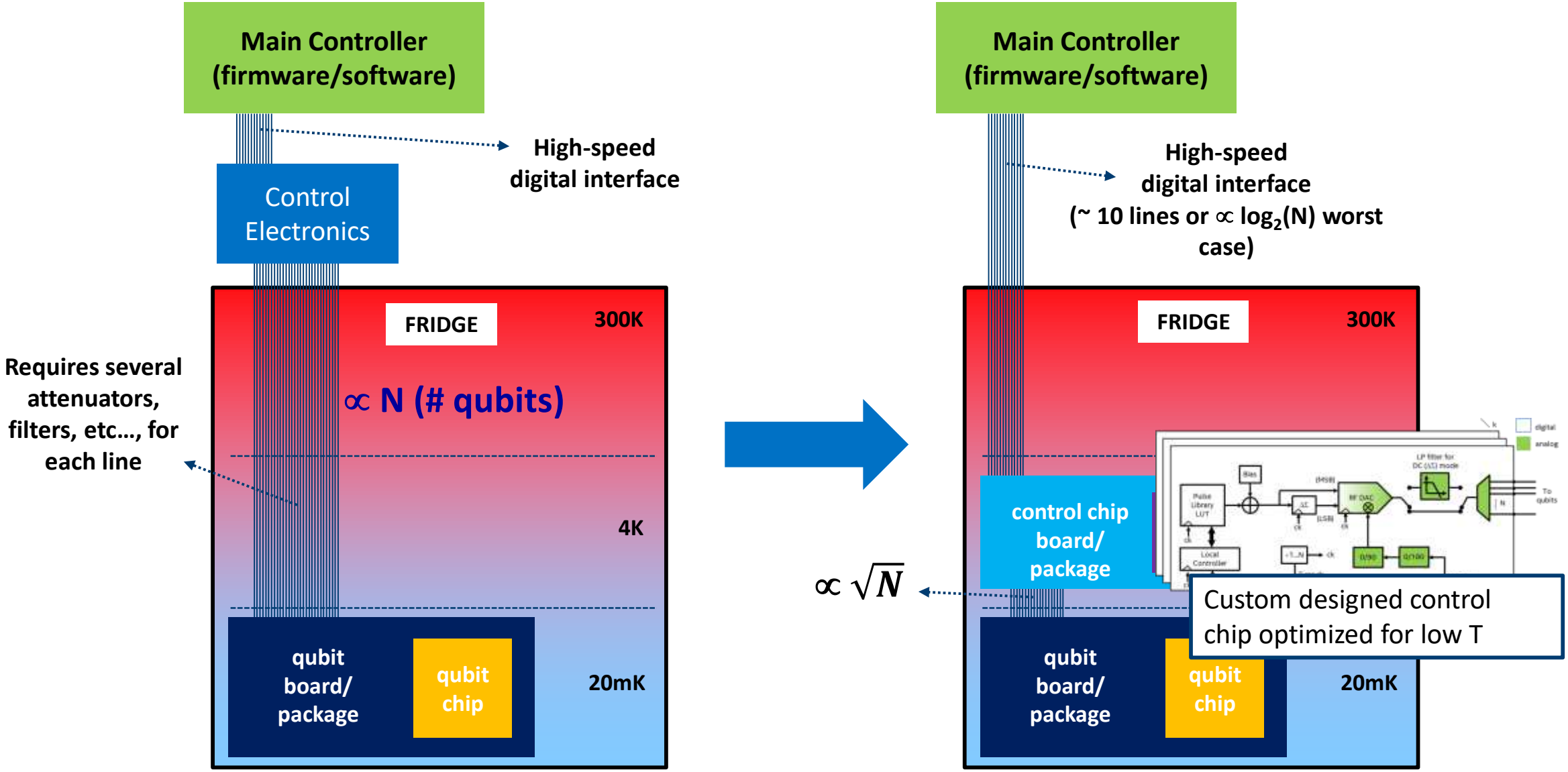
Processor
- 10^9 transistors
- 10^3 pins

3D NAND Memory
- 10^{12} bytes
- 10^2 pins

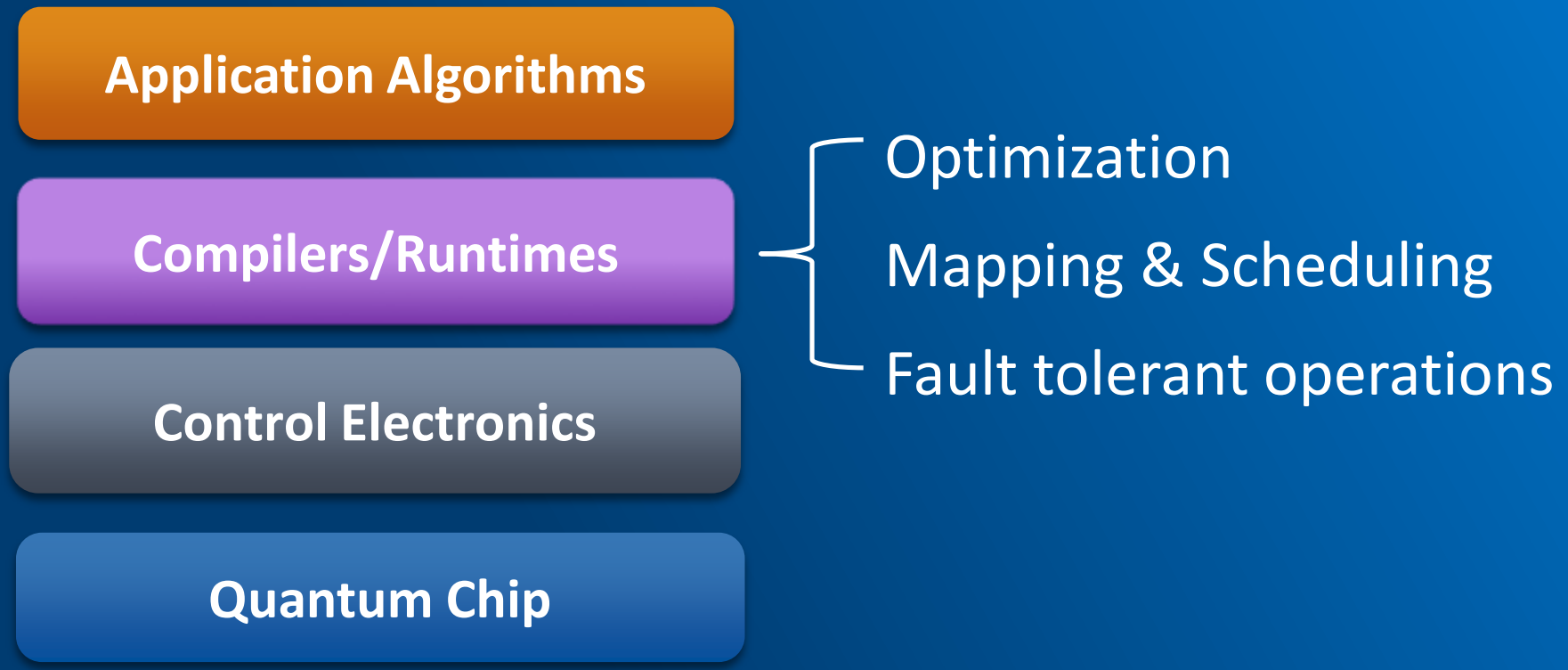


49-Qubit Transmon Array
- 49 qubits
- 108 pins

Solution Cryogenic Control



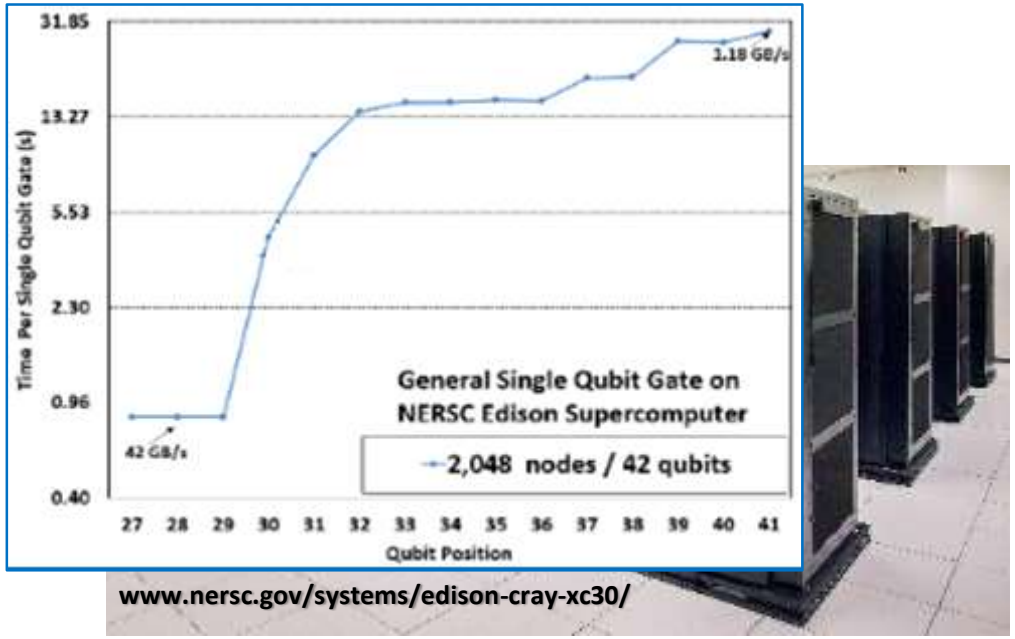
Developing a Quantum Computer System



QuBit Simulation

Universal: single and two-qubit controlled gates

High Perf QuBit Simulation



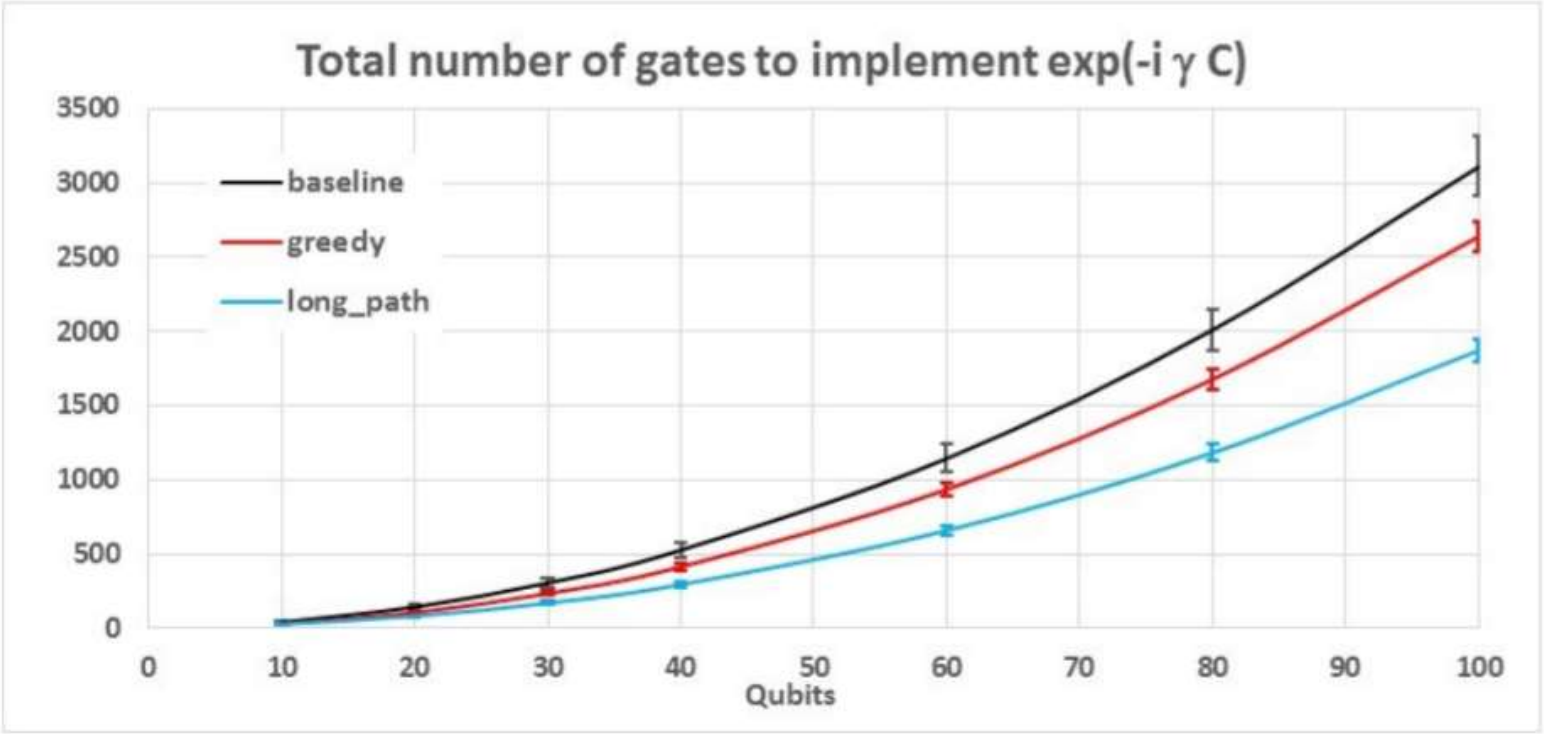
Open Source Release

External Collaboration: *Alan Aspuru-Guzik (Harvard), Matthias Troyer (ETH Zürich)*

Gate scheduling for quantum algorithms

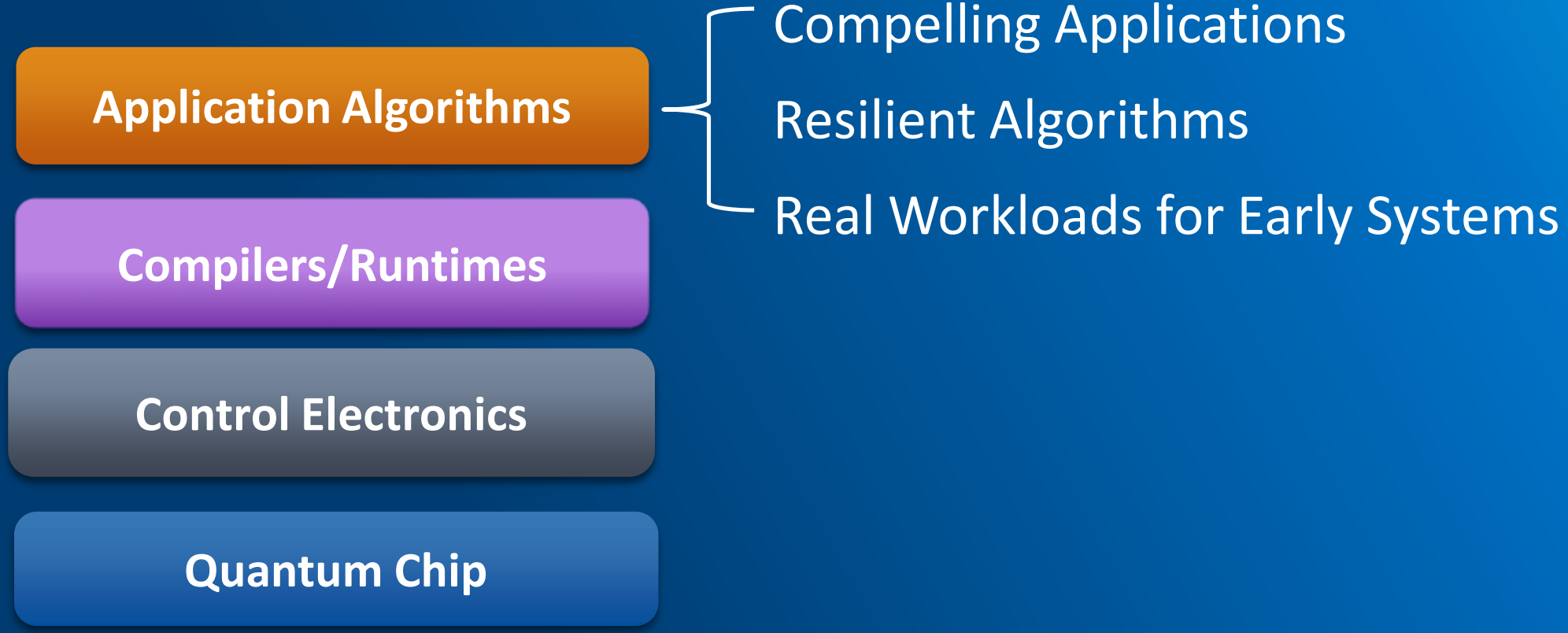
Mapping and scheduling under constraints:

- Logical dependency
- Exclusive activation
- Physical connectivity



Scheduling Quantum Approximate Optimization Algorithm for hardware with linear connectivity: three strategies of increasing sophistication

Developing a Quantum Computer System



Applications Space: HPC

Quantum co-processor: augmenting, not replacing, traditional HPC systems

~50+ Qubits: Proof of concept

- Computational power exceeds supercomputers
- Learning test bed for quantum “system”

~1000+ Qubits: Small problems

- Limited error correction
- Chemistry, materials design
- Optimization

~1M+ Qubits: Commercial scale

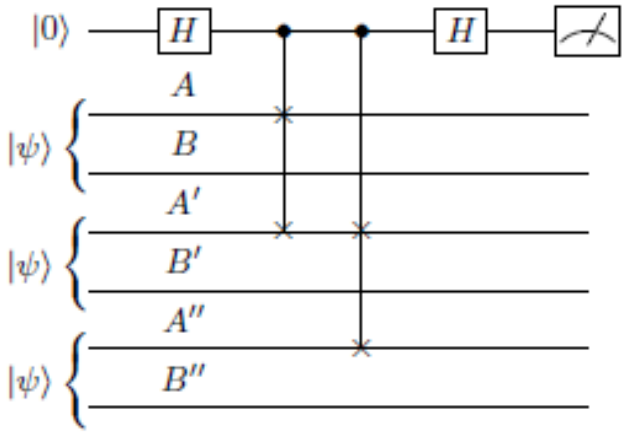
- Fault tolerant operation
- Cryptography
- Machine Learning

Materials Science

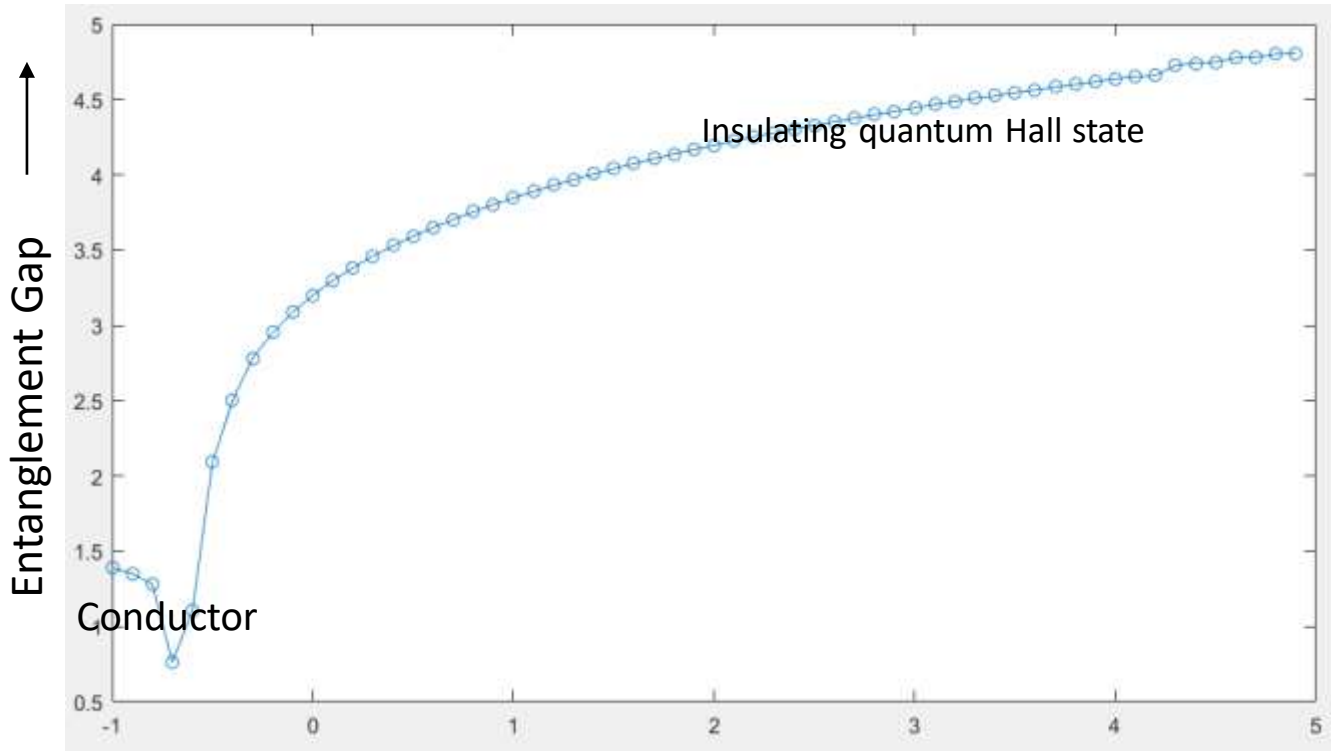
Quantifying entanglement provides a measurement of correlations between electrons which is useful for understanding the electronic properties of the material.

Algorithm to measure entanglement:

$$R_n = \langle\Psi|^{\otimes n} Perm_A |\Psi\rangle^{\otimes n}$$



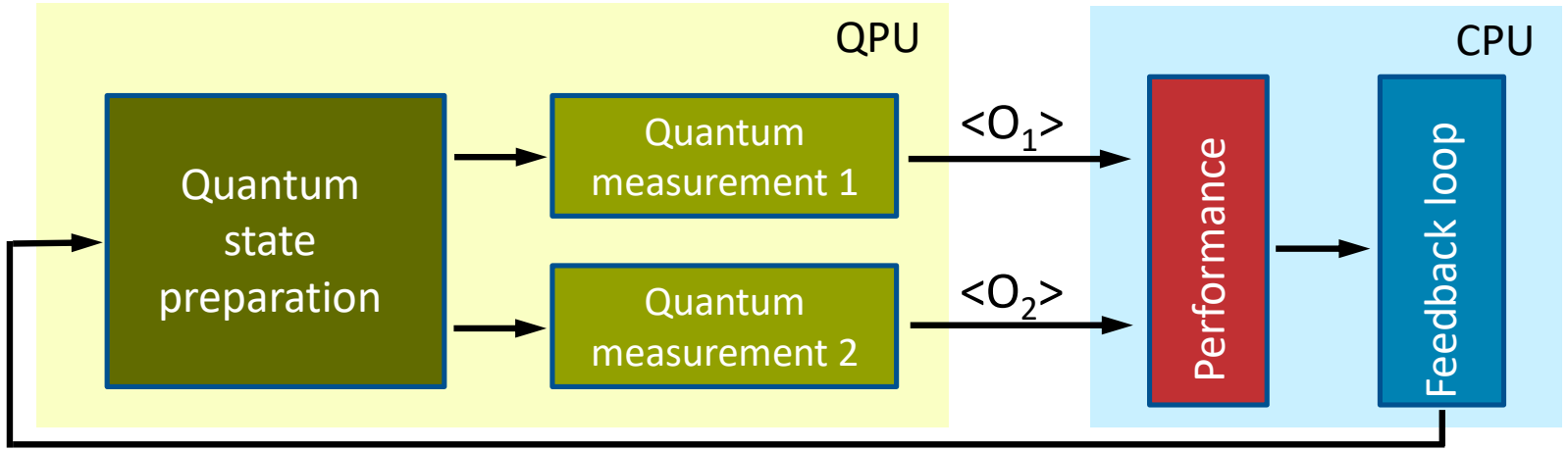
For example, in determining whether simulated material is a metal or an insulator.



Collaboration: *Damian Steiger, Matthias Troyer (ETH Zurich), Chris Monroe' (U of MD)*

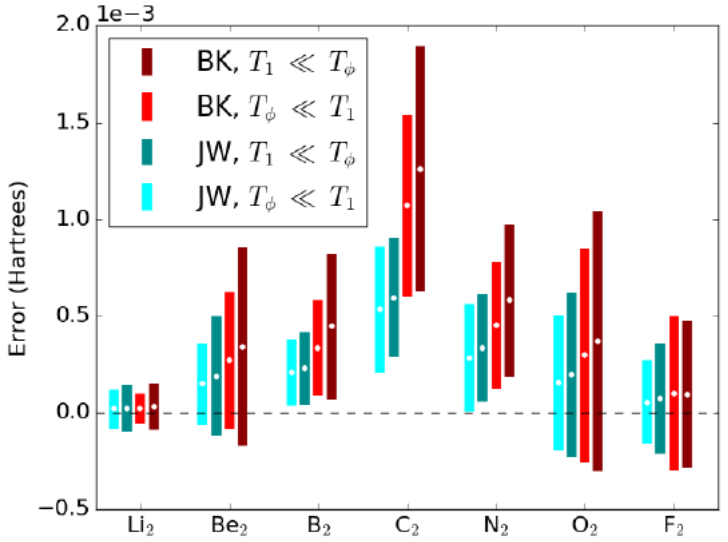
Resilient Algorithms

Hybrid quantum-classical



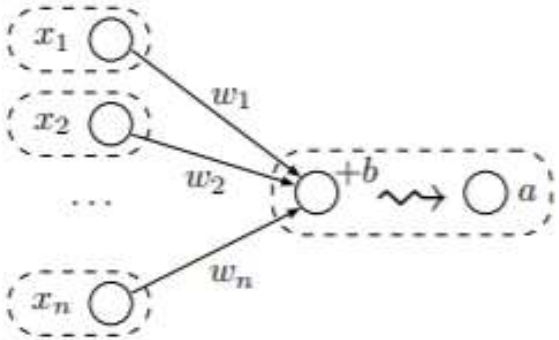
Quantum Chemistry and Noise study:

- Comparing two variants of the VQE algorithm to approximate lowest energy of molecules
- Surprisingly, version requiring more quantum operations is more resilient to noise

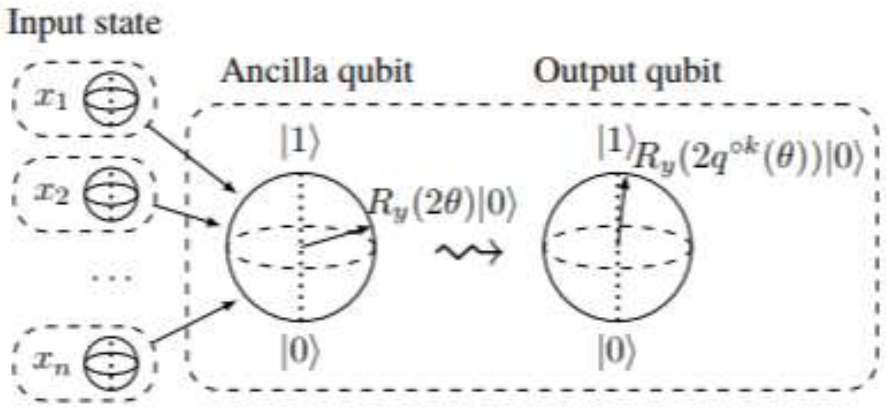


Collaboration: *Alan Aspuru-Guzik, Harvard, Jarrod McClean, LBL*

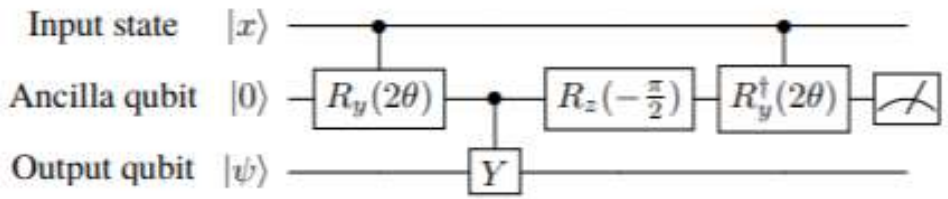
Machine Learning



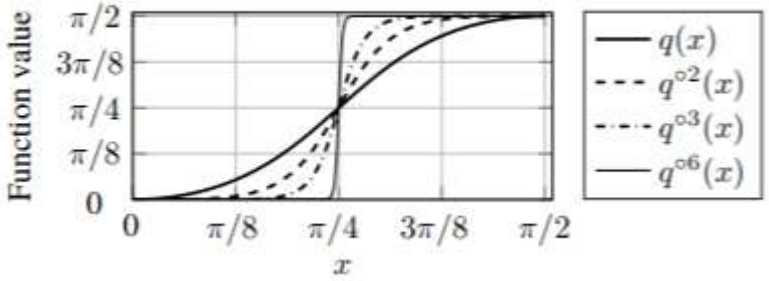
Classical Neuron



Quantum Neuron



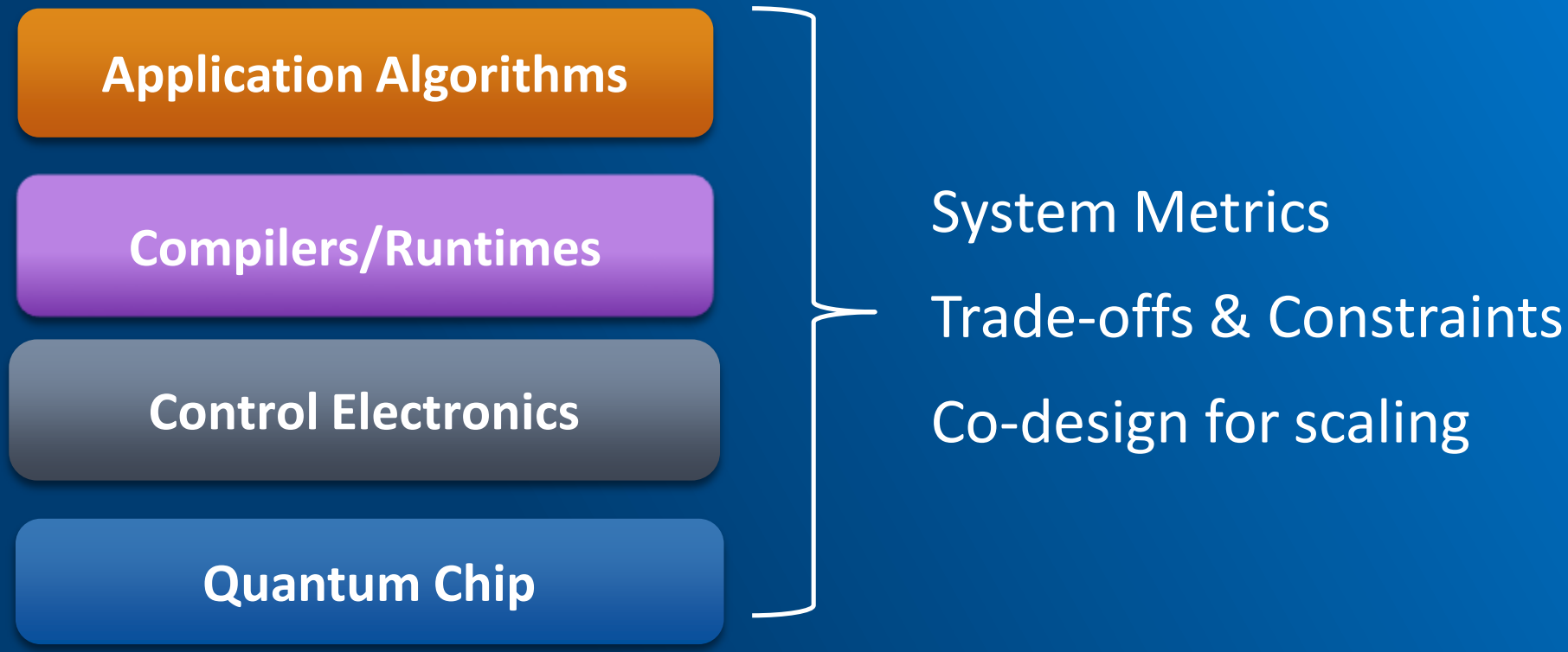
Repeat Until Success circuit



Non-linear Transfer Function

Collaboration: Yudong Cao and Alán Aspuru-Guzik, Harvard University

Developing a Quantum Computer System



Moving to System Level Metrics

Device-level metrics

- Physical qubit count
- Decoherence time T_1, T_2

System-level metrics

- Gate operation time
- Fidelity
- Logical qubit count
- Effective parallelization
- Utilization
- …

HW-SW co-design requires system metrics that impact real application performance

Conclusions

- The potential of quantum computing is generating tremendous excitement
- We're leveraging Intel's expertise in process and architecture to move faster
- A commercial system is ~10 Years Away

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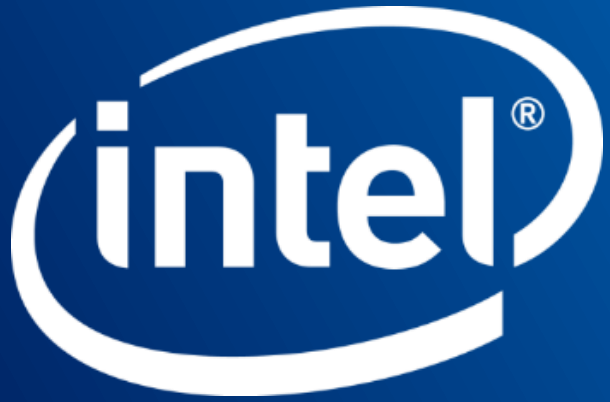
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