



Intel's approach to Quantum Computing

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Quantum Computing: Key Concepts

Superposition

Classical Physics



Heads or Tails

Quantum Physics



Heads and Tails

- 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

Entanglement



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

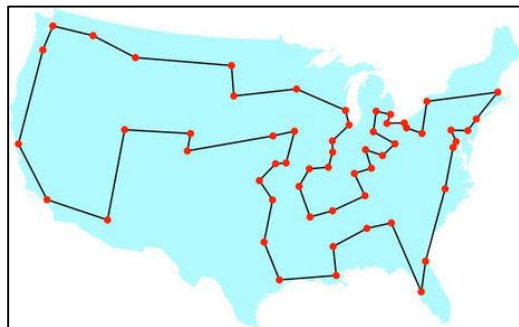
Fragility



**Observation or
noise
causes loss of
information**

Changing the World

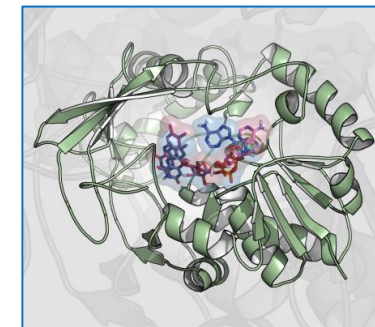
TIME
“Quantum
Will Change
Everything”



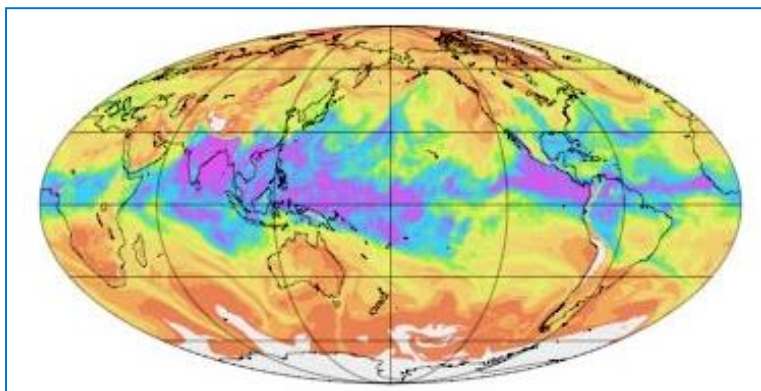
Travel and Logistics



Image Processing



Pharmacology



Improved Forecasting



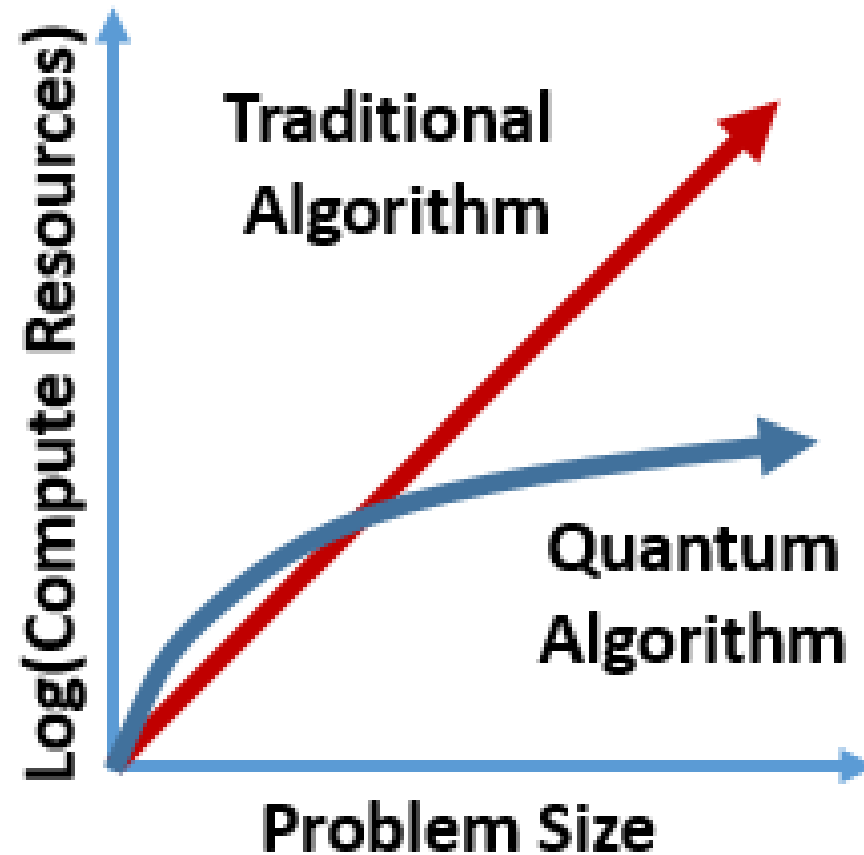
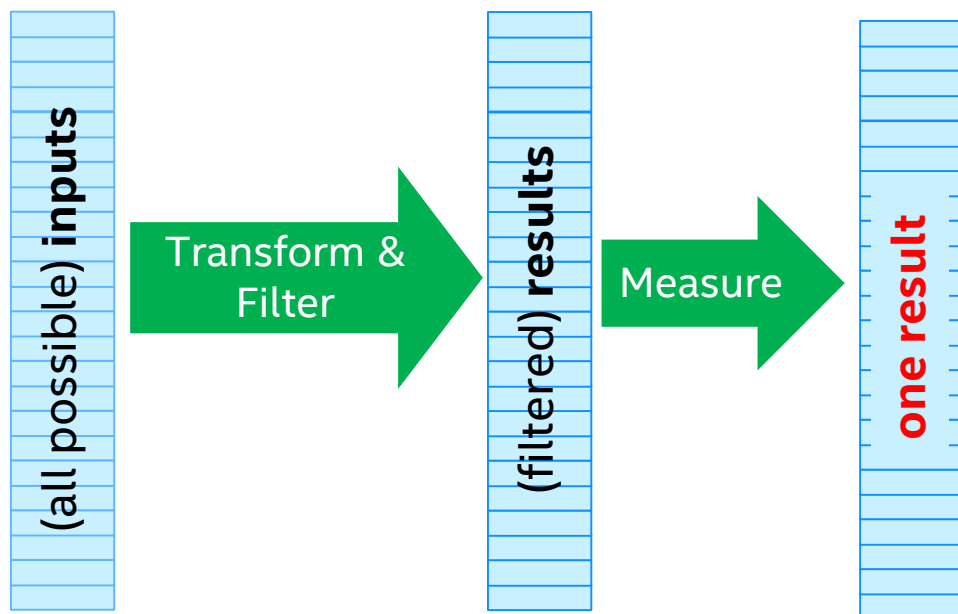
Improved Stock ROI



Cryptography

Source: Google Images

The promise of quantum computing



Exponential speedup \leftrightarrow surpassing the limits of scaling

Applications Space: High Performance Computing



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

Developing a Quantum Computer System





Intel – QuTech Research Collaboration

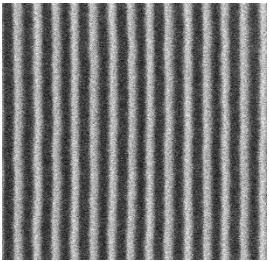


Intel Labs:

- Algorithms
- System Architecture
- Control Electronics

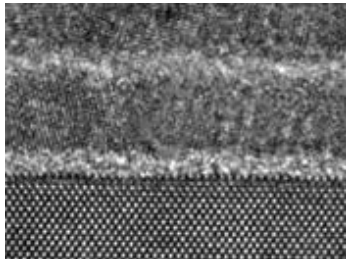
Intel TMG Components Research

Patterning



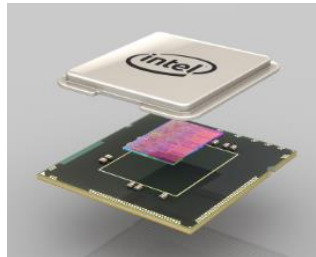
24nm Pitch Lines

Atomic Layer Control



Metal Gate / High k on
300mm Silicon Wafer

Packaging



Assembly and Packaging
Research

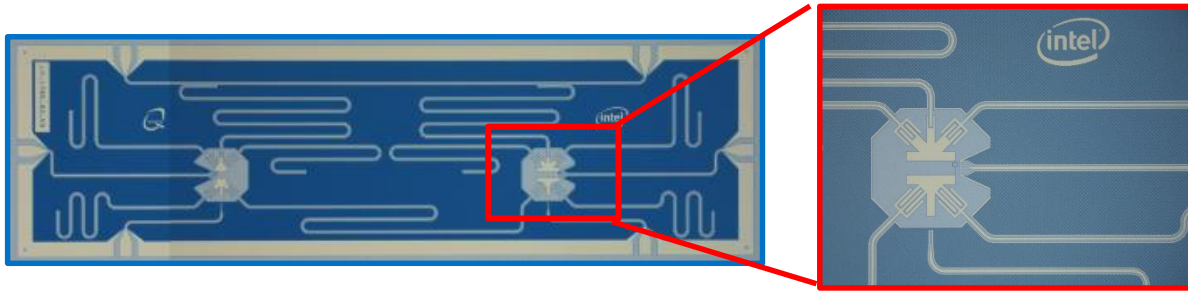


QuTech's Expertise in qubit
operation and control

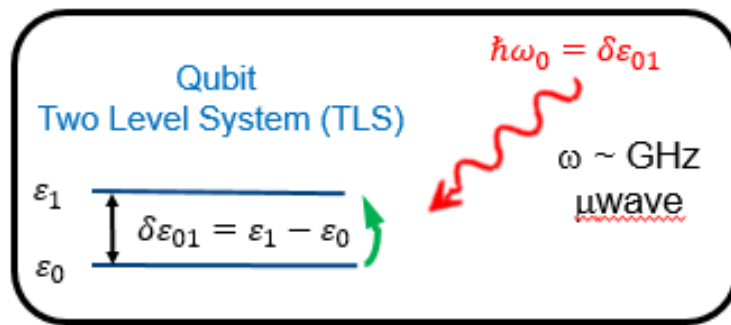
Combining Intel capabilities with Delft expertise

Building Better Qubits

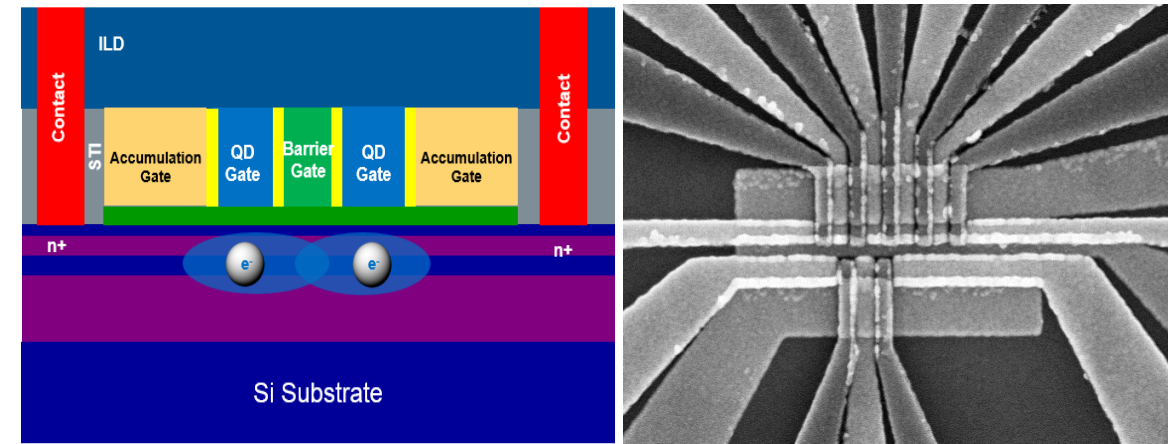
Superconducting Qubits



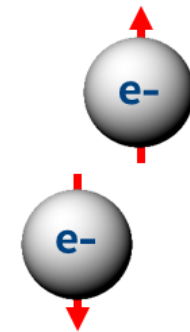
Very high
quality
microwave
circuit



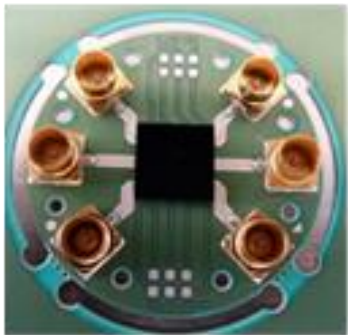
Spin Qubits in Silicon



Single electron
transistors, where
qubit is spin state



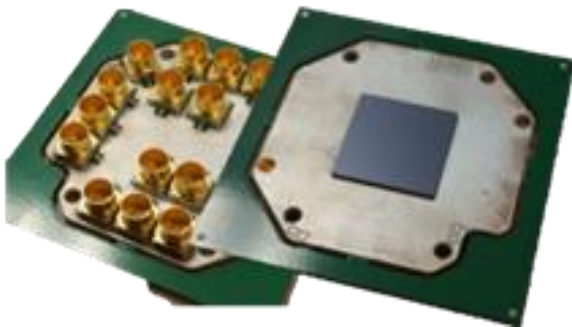
Superconducting Qubit Progress



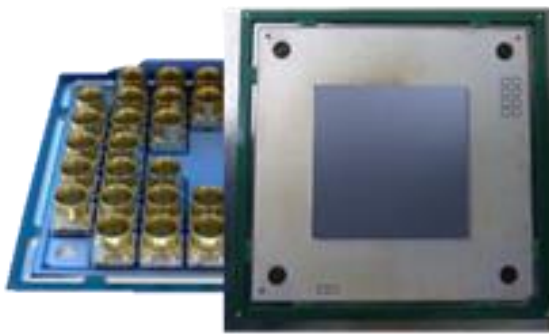
Resonator



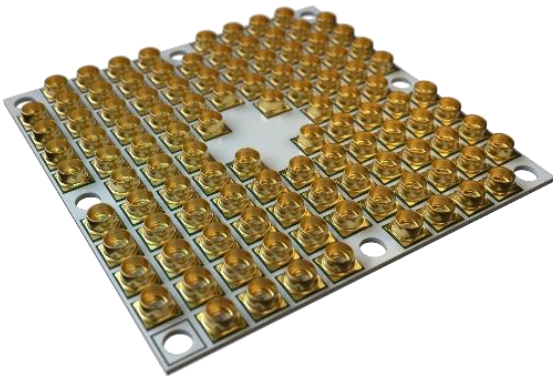
6 Qubits



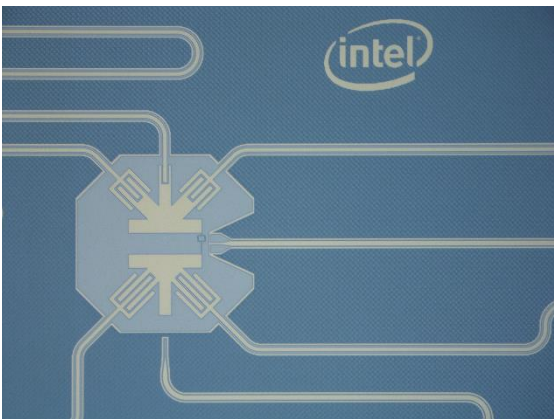
7 Qubit Array



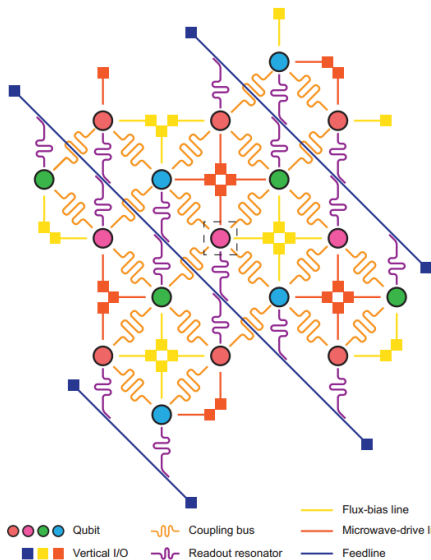
17 Qubit Array



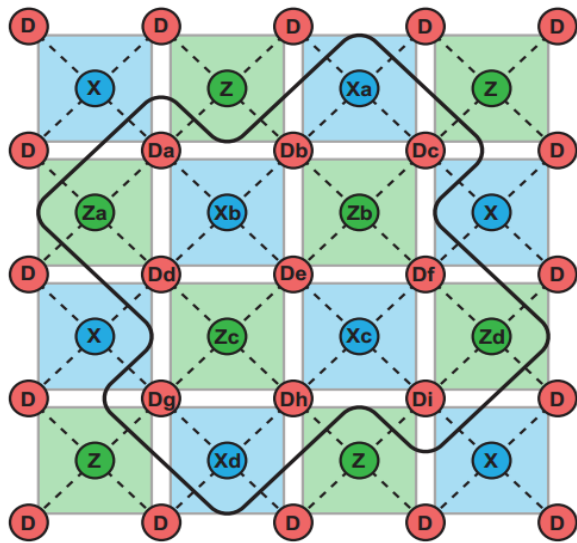
Tangle Lake (49 Qubits)



Starmon Geometry
with up to 30us T1

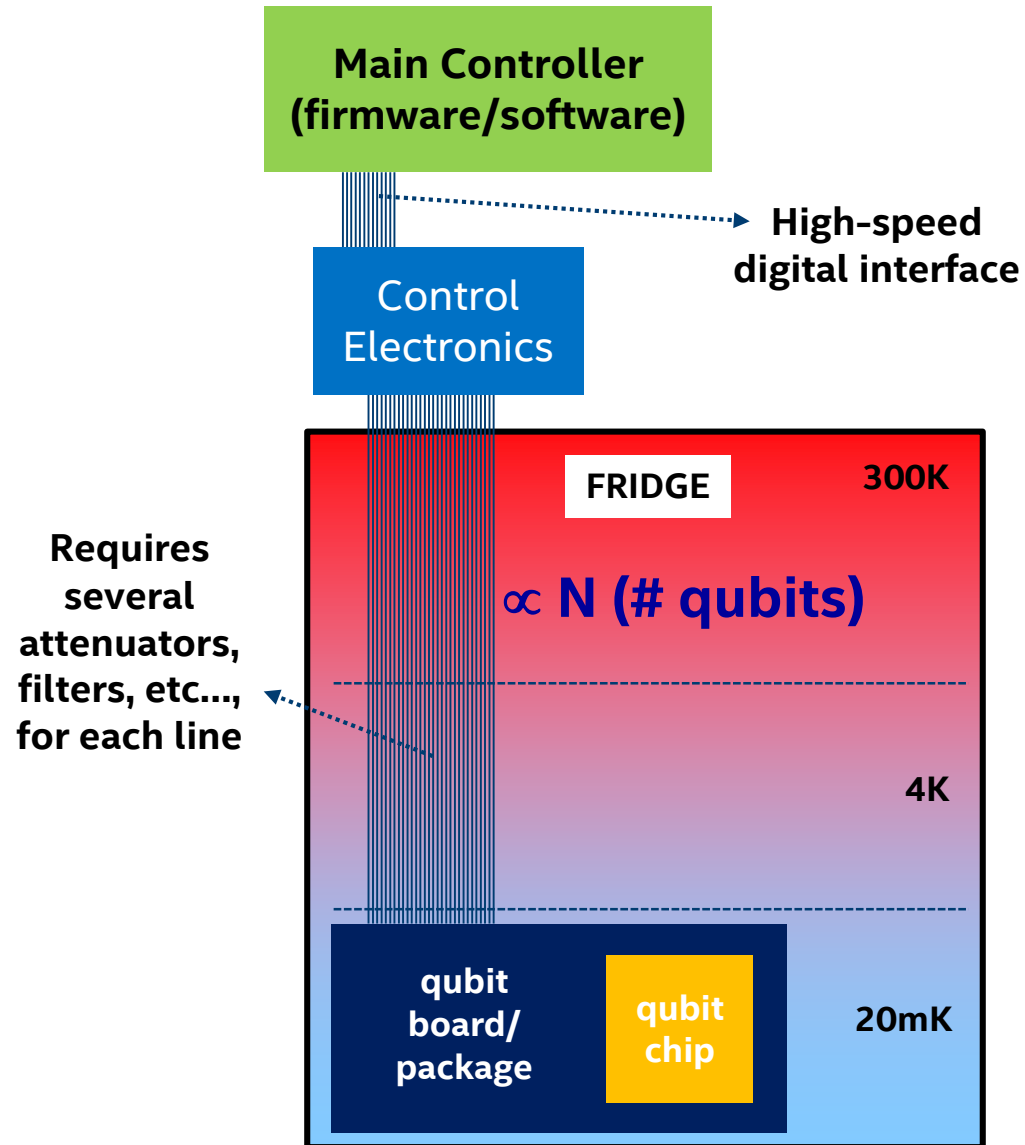


Shared Feedlines

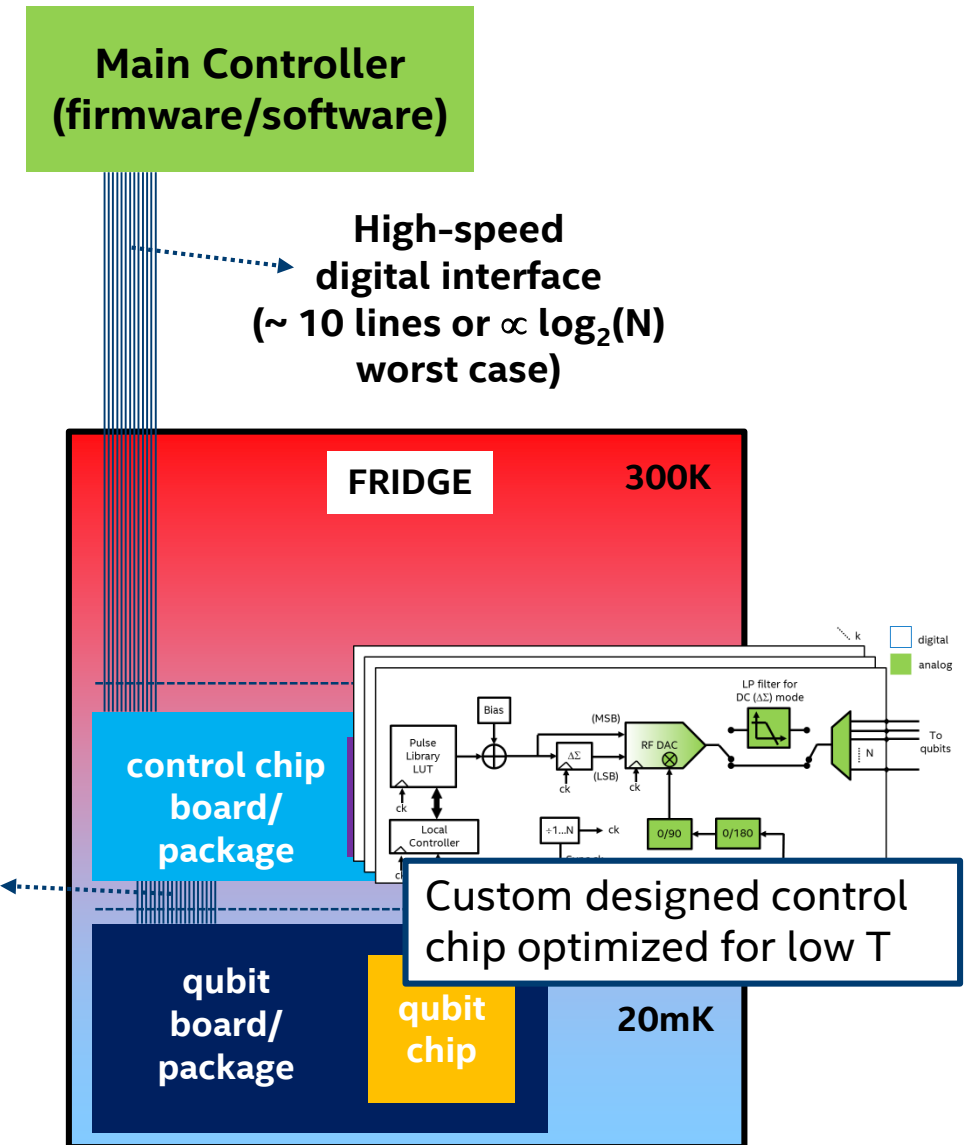


Surface Code Topology

Cryogenic Control



$$\propto \sqrt{N}$$

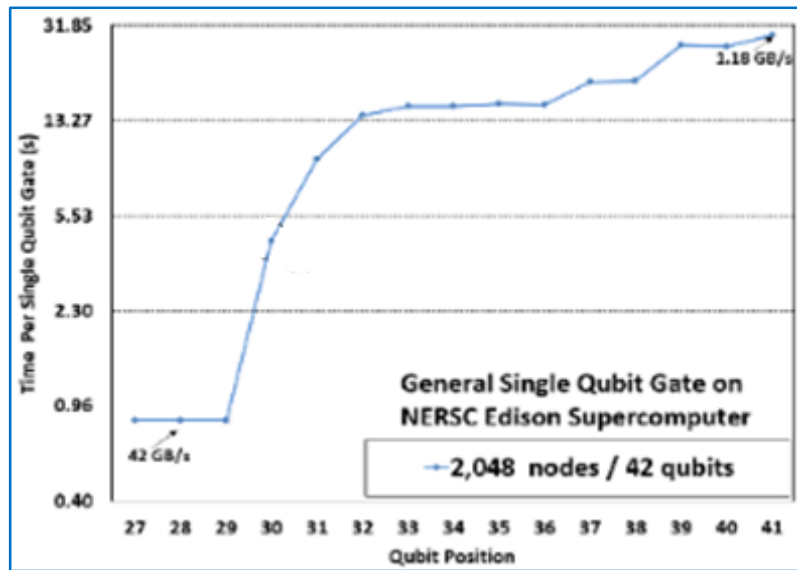


QuBit Simulation

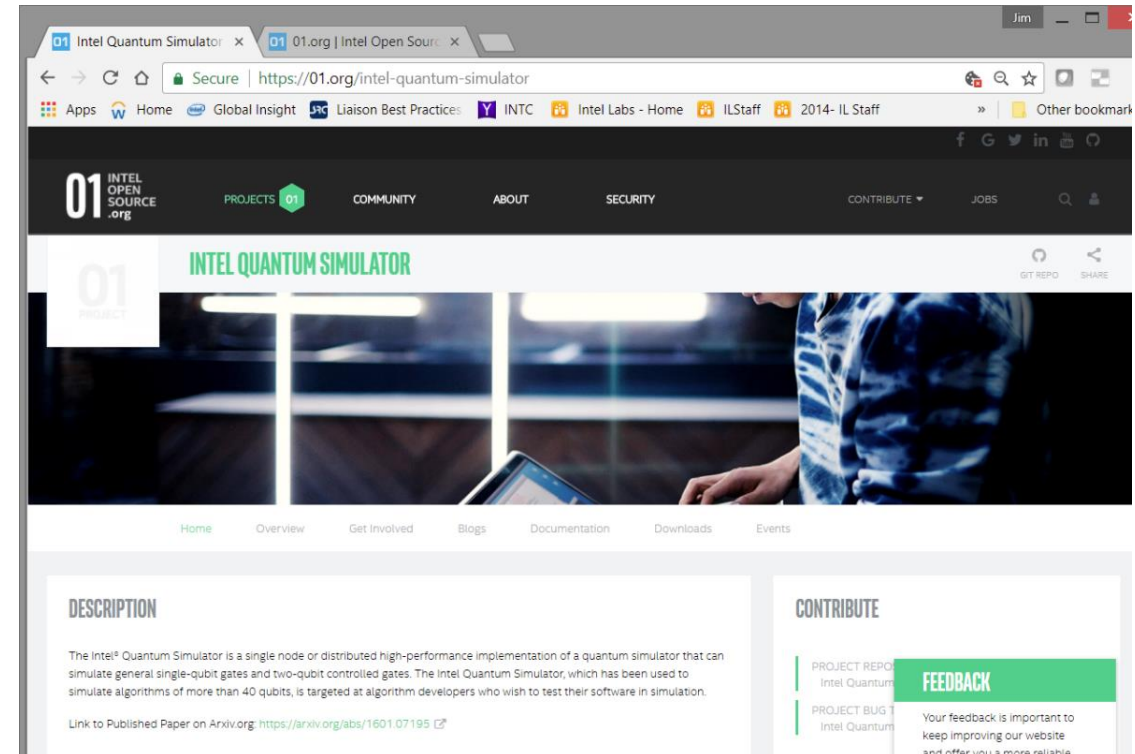
Universal: single and two-qubit controlled gates

Open Source Release

High Perf QuBit Simulation



www.nersc.gov/systems/edison-cray-xc30/



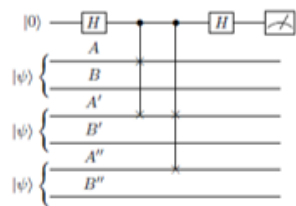
External Collaboration: Alan Aspuru-Guzik (Harvard), Matthias Troyer (ETH Zürich)

Quantum Computing: Algorithms and Applications

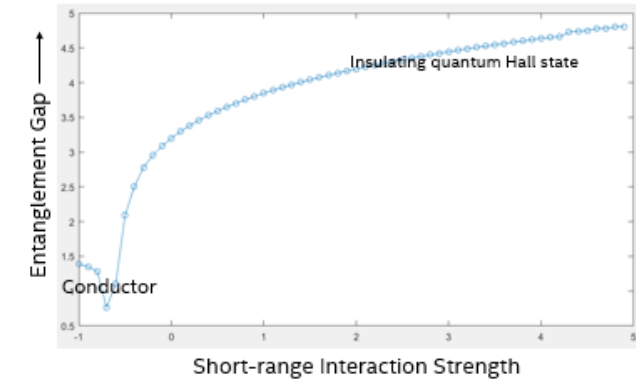
Materials Science

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

Algorithm to measure entanglement:
 $R_n = \langle \Psi | \otimes^n \text{Perm}_A | \Psi \rangle^{\otimes n}$



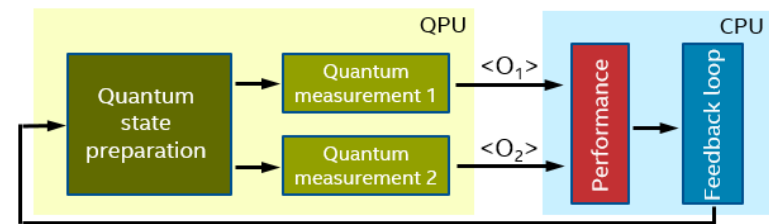
For example, in determining whether simulated material is a metal or an insulator.



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

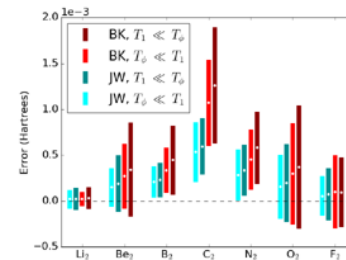
Resilient Algorithms

Hybrid quantum-classical



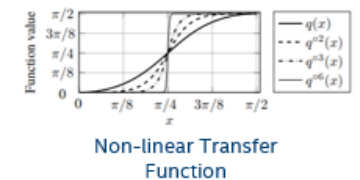
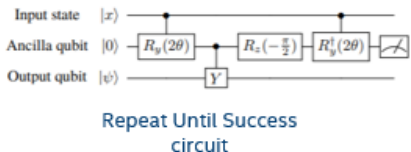
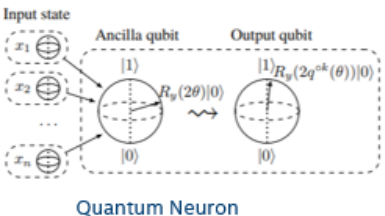
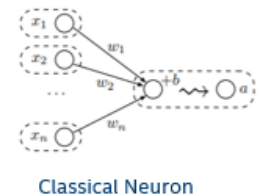
Quantum Chemistry and Noise study:

- 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



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



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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