IMPACT
.TECH

The Arrival of Quantum Computing

Will Zeng
Head of Quantum Cloud Services, Rigetti Computing

Keeping up with the Quantashians

Will Zeng
Rigetti Computing

Impact.Tech
April 19, 2018

@wjzeng

Quantum Computing

If there is a sense of reality, then there must also be a sense of possibility

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Part 1. The Tech:

Why build a quantum computer at all?

Why are we able to build them today?

Upcoming Tech milestones to watch.

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Rampant discussion #1 **

** hard limit of one question on the multiverse or whether we live in a simulation

Part 1. The Tech:

Why build a quantum computer at all?
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Upcoming Tech milestones to watch.

Rampant discussion #1 **

Part 2. The Industry:

What is the quantum industry and what is its trajectory?
What is the customer landscape?
How do I get involved as a
{scientist, programmer, entrepreneur, investor}?

Rampant discussion #2

** hard limit of one question on the multiverse or whether we live in a simulation

Part 1. The Tech

Why build a quantum computer at all?

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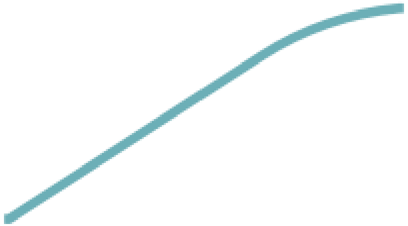
Upcoming Tech milestones to watch.

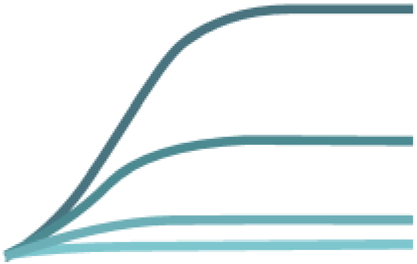
Classical computers have fundamental limits



Transistor scaling

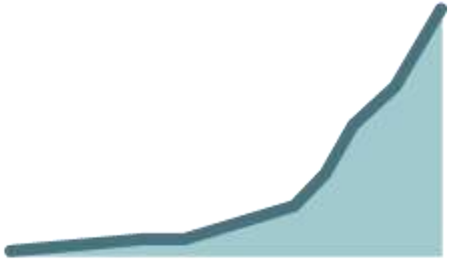
Economic limits with 10bn for next node fab

Ultimate single-atom limits



Returns to parallelization

Amdahl's law



Energy consumption

Exascale computing project has its own power plant

Power density can melt chips

And there's more we want to do

Simulation Driven Drug Design

Organic Batteries & Solar Cells

Artificial General Intelligence

Why build a quantum computer?

New power | New opportunity | Fundamental curiosity

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Quantum computing power* scales exponentially with qubits
N bits can exactly simulate log N qubits

* We will be more precise later in the talk

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This compute unit....

Commodore 64

can exactly simulate: **10 Qubits**

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Rigetti 19 qubits
available since Dec 2017

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Why build a quantum computer?

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For **N qubits** every time step (~100ns*) is an exponentially large **2^N x 2^N** complex **matrix multiplication**

* for superconducting qubit systems

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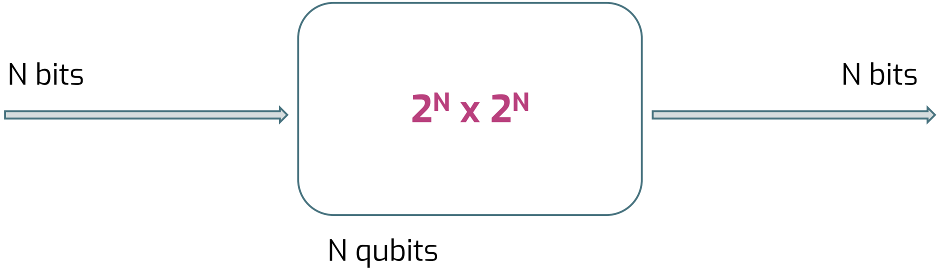
The “big-memory small pipe” mental model for quantum computing



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Why build a quantum computer?

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Machine Learning

> Development of new training sets and algorithms

> Classification and sampling of large data sets

Supply Chain Optimization

> Forecast and optimize for future inventory demand

> NP-hard scheduling and logistics map into quantum applications

Robotic Manufacturing

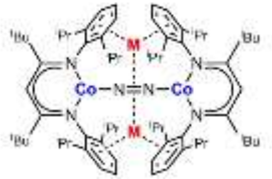
> Reduce manufacturing time and cost

> Maps to a Traveling Salesman Problem addressable by quantum constrained optimization

Computational Materials Science

> Design of better catalysts for batteries

> Quantum algorithms for calculating electronic structure



Alternative Energy Research

> Efficiently convert atmospheric CO_2 to methanol

> Powered by existing hybrid quantum-classical algorithms + machine learning

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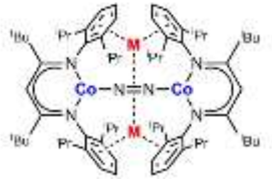

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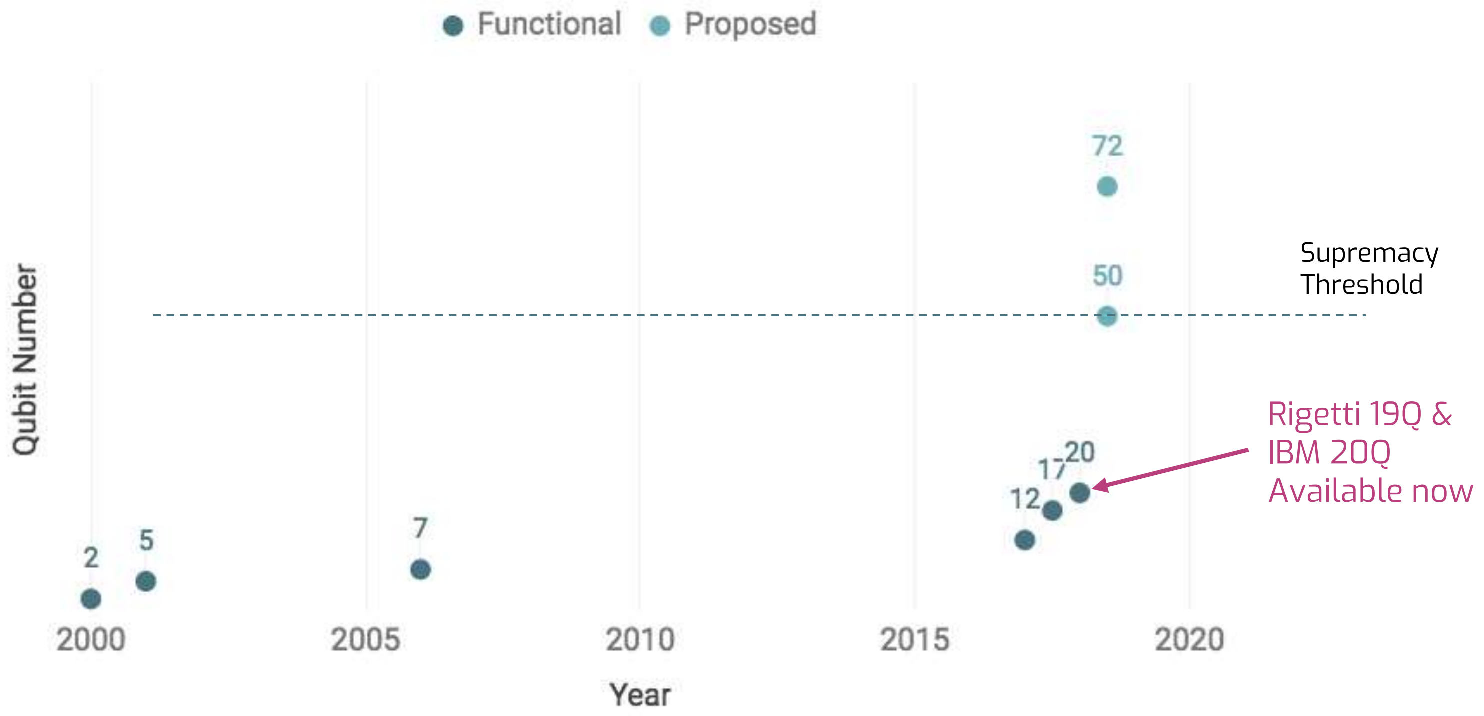
What isn't on here: breaking RSA with Shor's algorithm

Why build a quantum computer?

New power | **New opportunity** | Fundamental curiosity

Quantum processors are scaling up quickly



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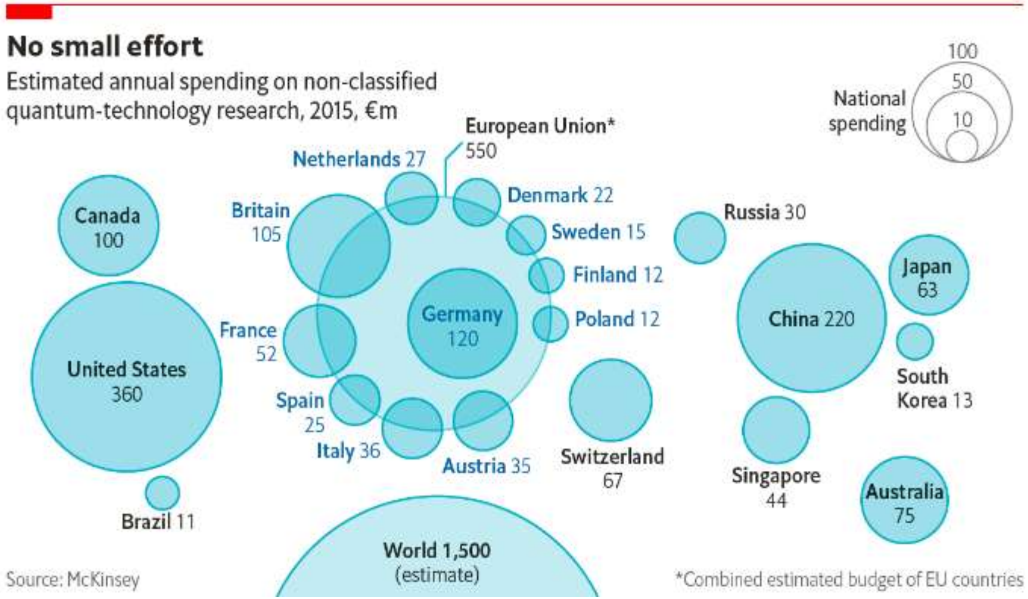
Investments across academia, government, and industry are global and growing



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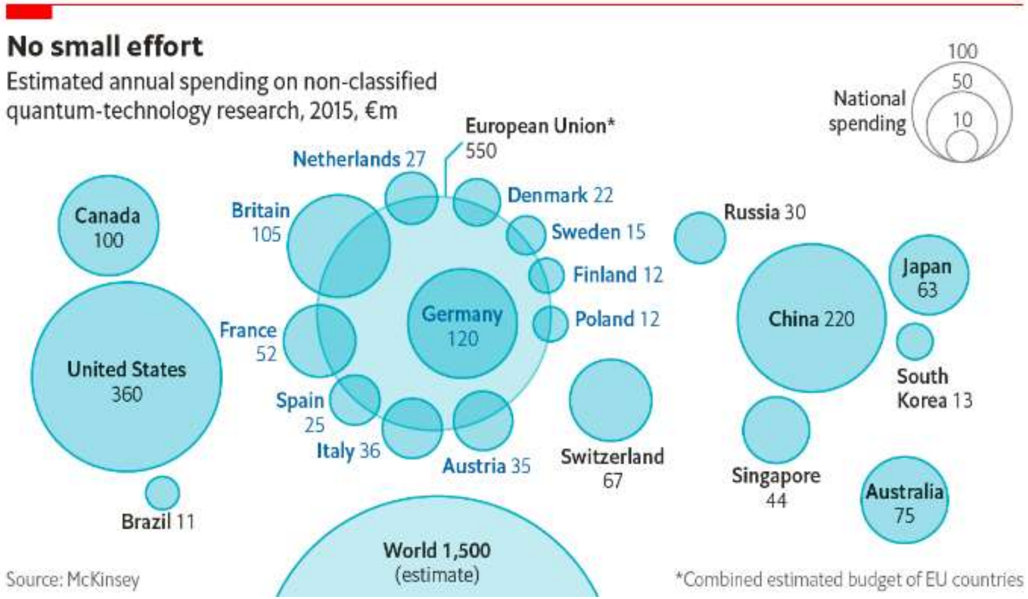
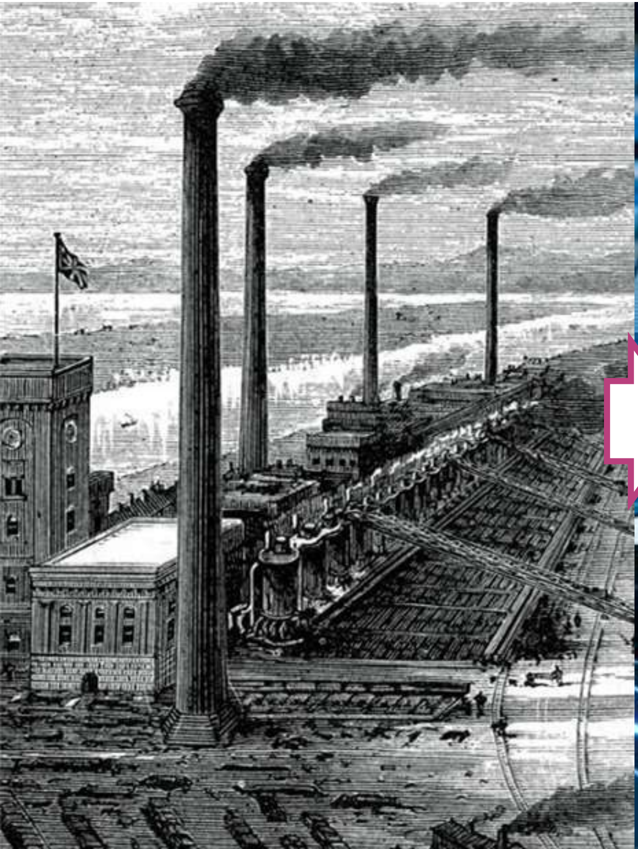
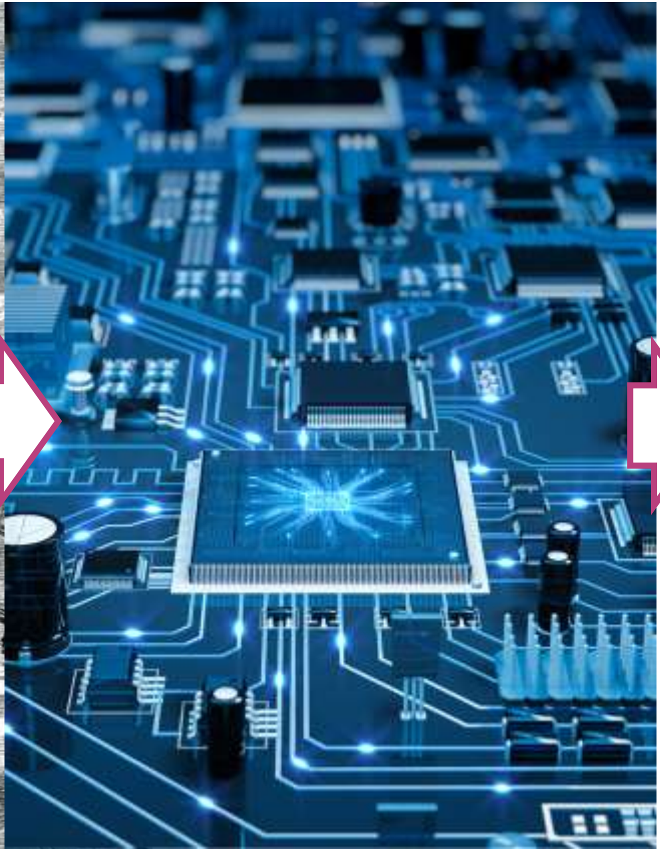


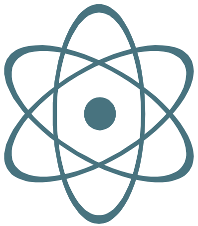
Plus approximately $300M in global VC investment

Why build a quantum computer?

New power | New opportunity | **Fundamental curiosity**







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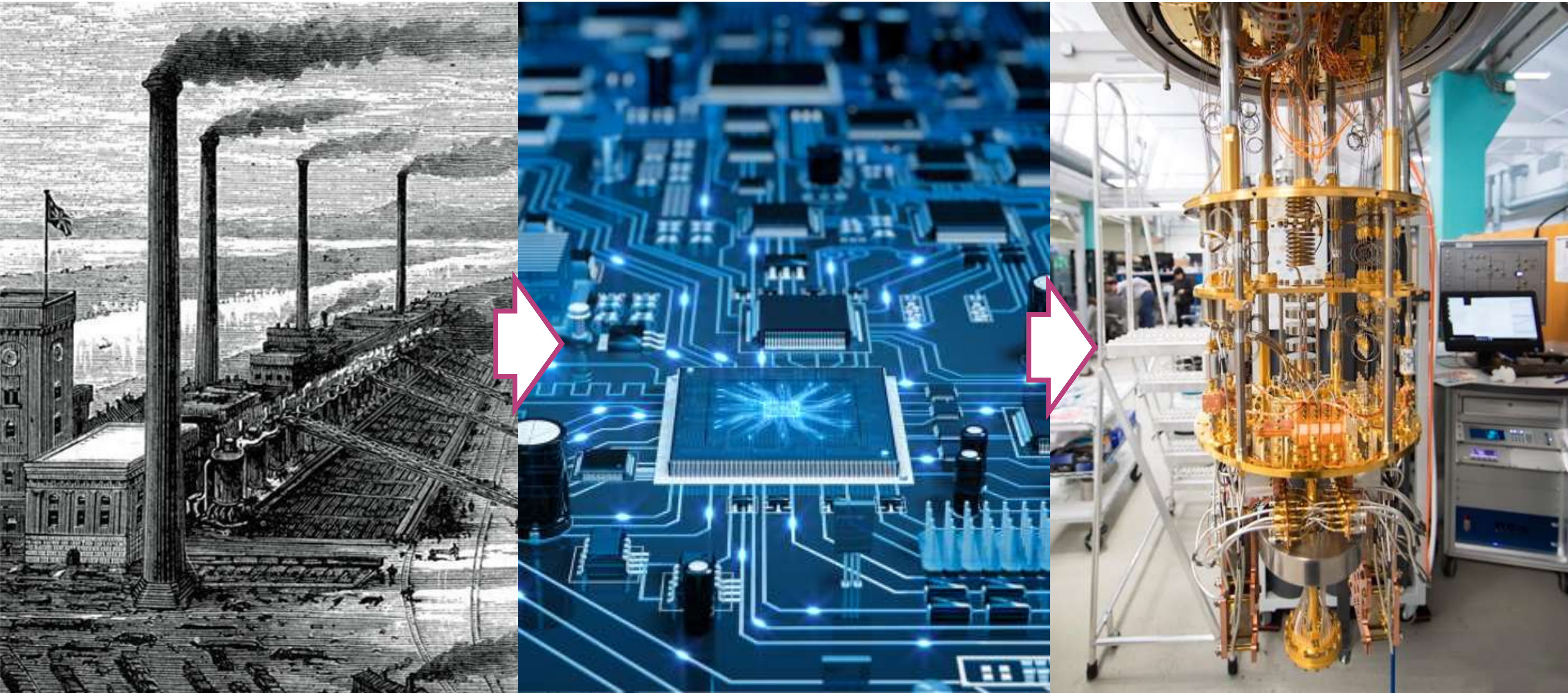

Why build a quantum computer?

New power | New opportunity | **Fundamental curiosity**

Quantum computing reorients the relationship between physics and computer science.

Every "function which would ***naturally*** *be regarded as computable" can be computed by the universal Turing machine.* - Turing

"... ***nature*** *isn't classical, dammit..."* - Feynman

Why build a quantum computer?

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*Every "function which would **naturally** be regarded as computable" can be computed by the universal Turing machine.* - Turing

*"... **nature** isn't classical, dammit..."* - Feynman

Physical phenomenon apply to information and computation as well.

> Superposition

> No-cloning

> Teleportation

Why build a quantum computer today?

Scalable hardware | Robust algorithms

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Quantum + Computer

Isolated

Long-lived coherence

Not necessarily microscopic

Fundamentally controllable

Simple scalable building blocks

Programmable

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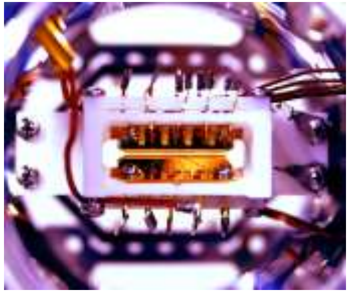
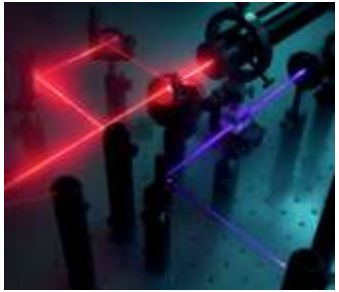
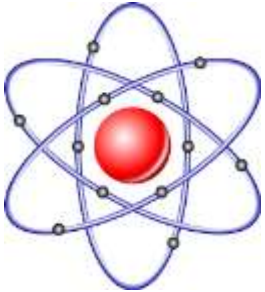
(1994-2010)



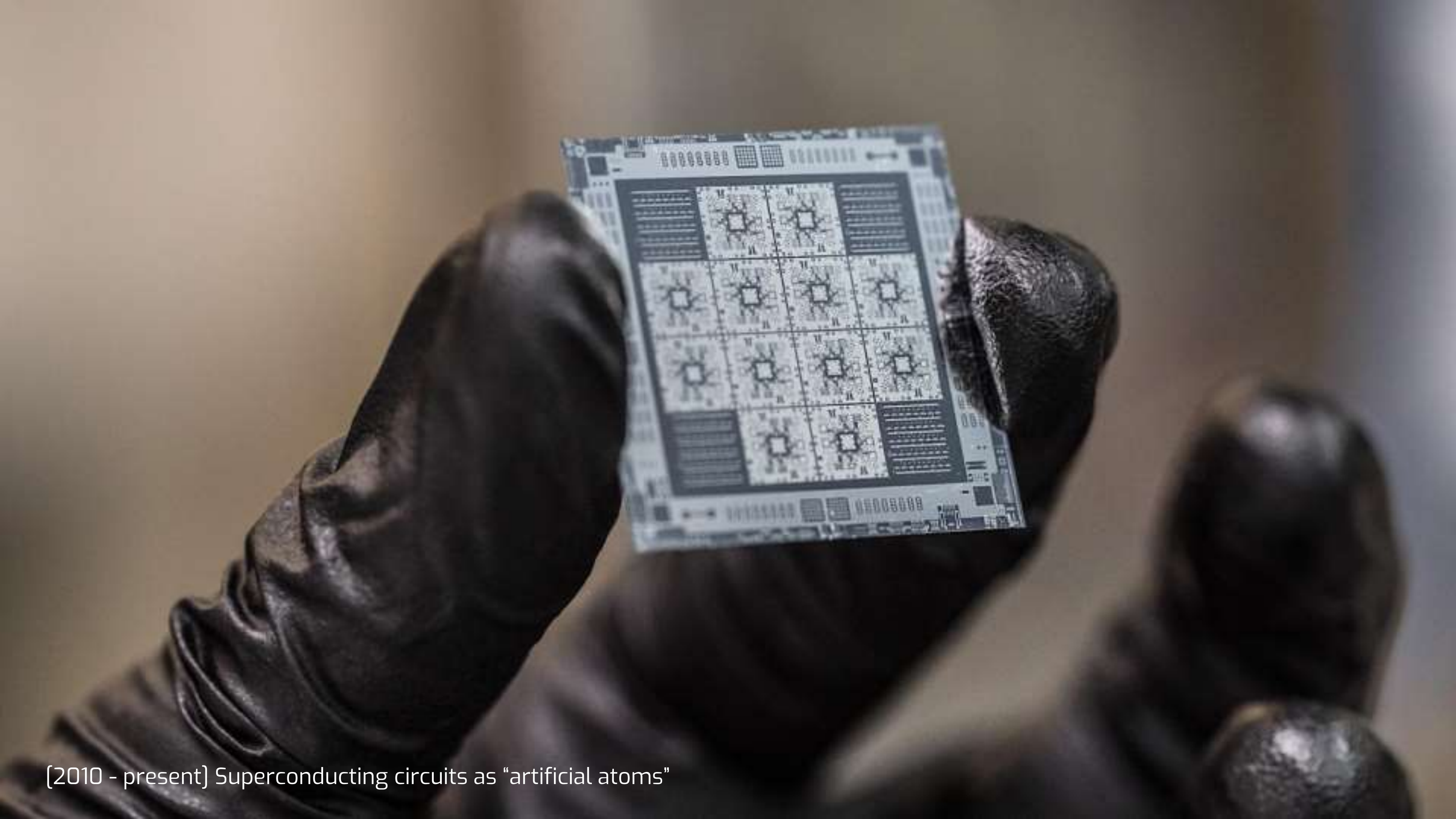
Ion Traps



Photonic Networks



Nuclear Magnetic Resonance



(2010 - present) Superconducting circuits as “artificial atoms”

Why build a quantum computer today?

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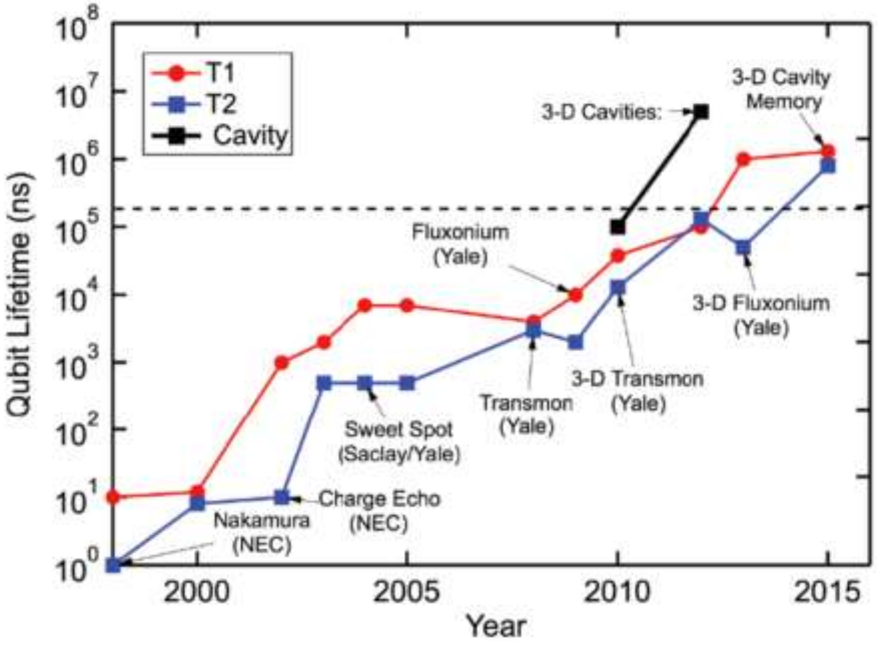
Superconducting qubit performance has increased by 10,000,000x in the last 15 years



M.Reagor thesis, 2015

Why build a quantum computer today?

Scalable hardware | **Robust algorithms**

1994

Why build a quantum computer today?

Scalable hardware | **Robust algorithms**

1992-4
First Quantum Algorithms w/ Exponential Speedup
(Deutsch-Jozsa, Shor's Factoring, Discrete Log, ...)

1996
First Quantum Database Search Algorithm (Grover's)

TODAY

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O(log N)

O(√N)

Big proven speedups

> Breaking RSA
> Database search
> Crypto

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Quantum Algorithms for SVM's & Principal Component Analysis

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$O(\sqrt{N})$

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Big proven speedups

> Breaking RSA
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These algorithms require Big, Perfect Quantum Computers ™

> 10,000,000 qubits for Shor's algorithms
to factor a 2048 bit number

TODAY

Why build a quantum computer today?

Scalable hardware | **Robust algorithms**

We have Small, Noisy Quantum Computers ™

Chance of hardware error in a classical computer:

0.000,000,000,000,000,000,000,1 %

Chance of hardware error in a quantum computer:

0.1%

Why build a quantum computer today?

Scalable hardware | **Robust algorithms**

We have Small, Noisy Quantum Computers ™

Chance of hardware error in a classical computer:

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NISQ:
Noisy, intermediate scale quantum computing

Chance of hardware error in a quantum computer:

0.1%

Preskill 2018. Quantum Computing in the NISQ era and beyond (arXiv: 1801.00862)

1994

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TODAY

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2013
Practical Quantum Chemistry Algorithms (VQE)

2016
Practical Quantum Optimization Algorithms (QAOA)
Simulations on Near-term Quantum Supremacy

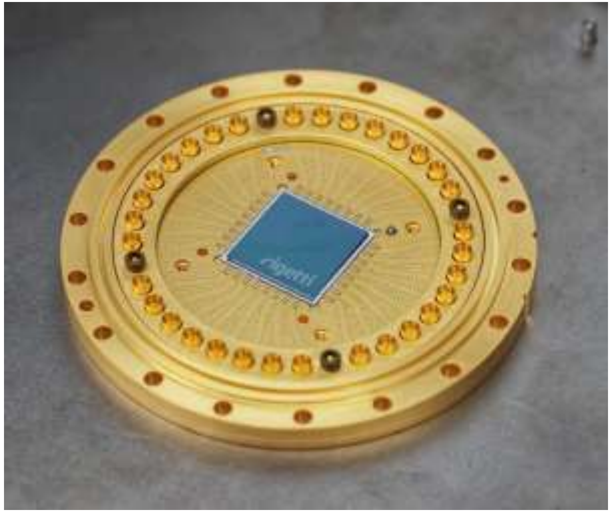
TODAY

Hybrid quantum/classical algs

> Noise Robust
> Empirical speedups

Useful quantum computation is **hybrid**

Quantum computers have quantum processor(s) and classical processors



Quantum processor

Full quantum computing system

Otterbach et al. arXiv:1712.05771

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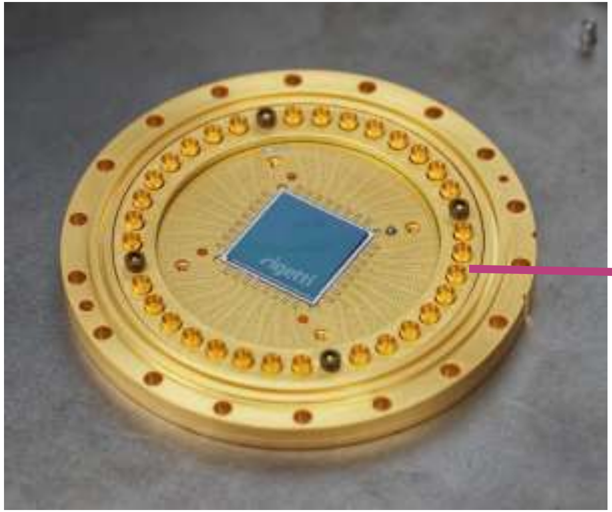

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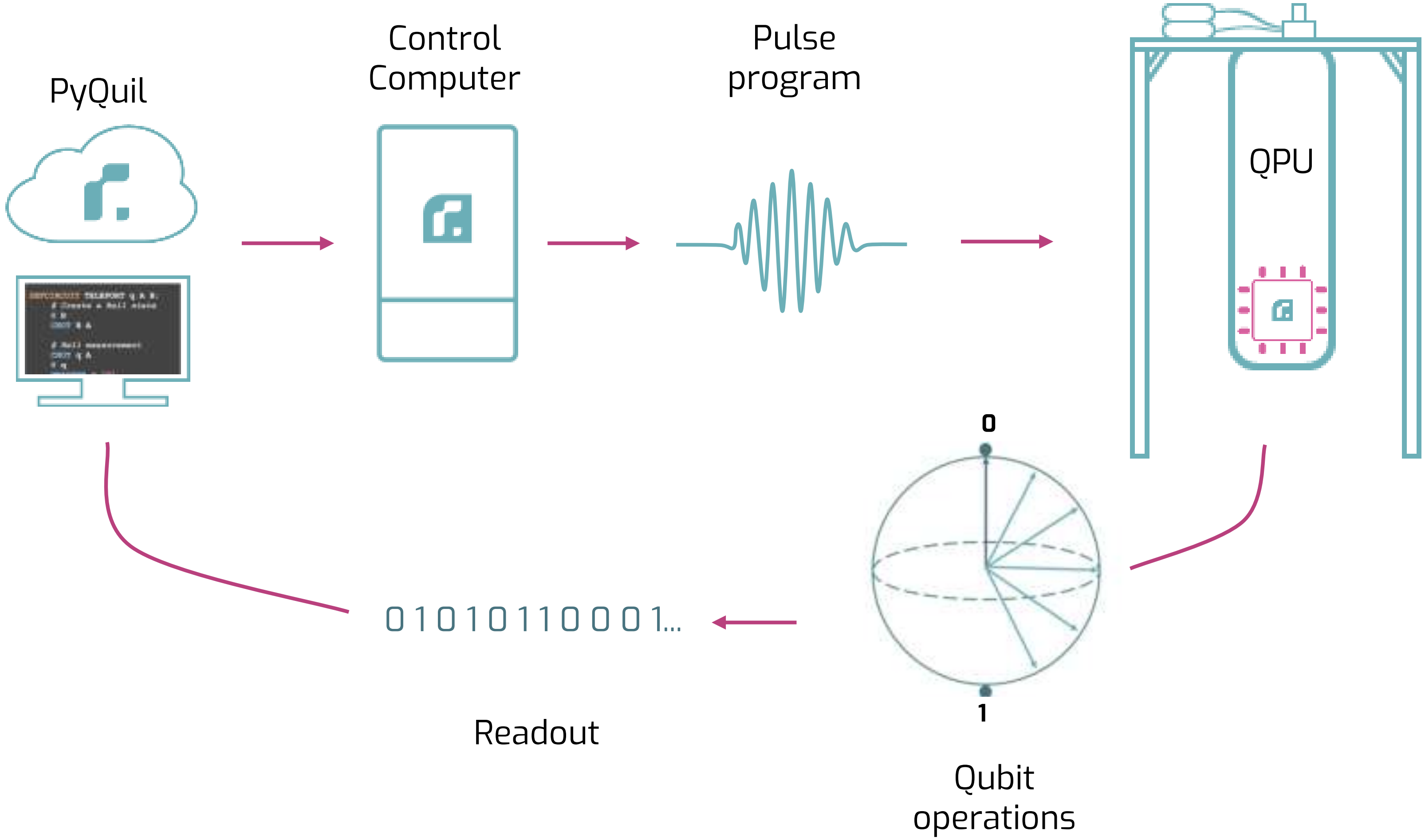
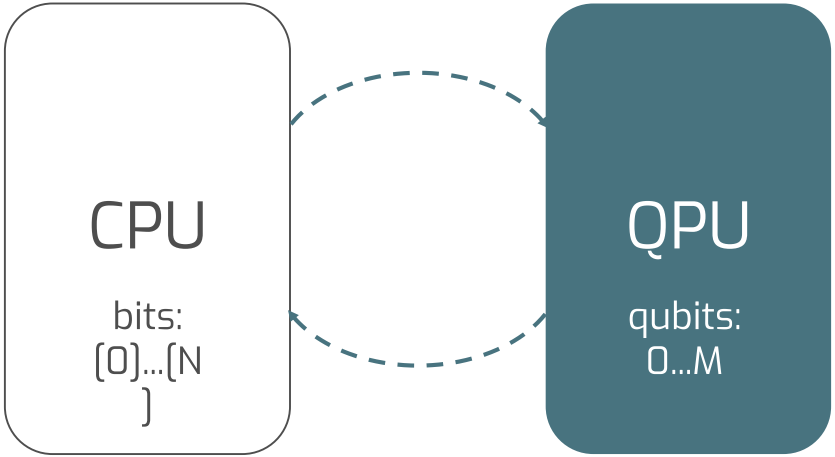


PyQuil
Control Computer
Pulse program
QPU
0
1
Qubit operations
0 1 0 1 0 1 1 0 0 0 1...
Readout

Useful quantum computation is **hybrid**

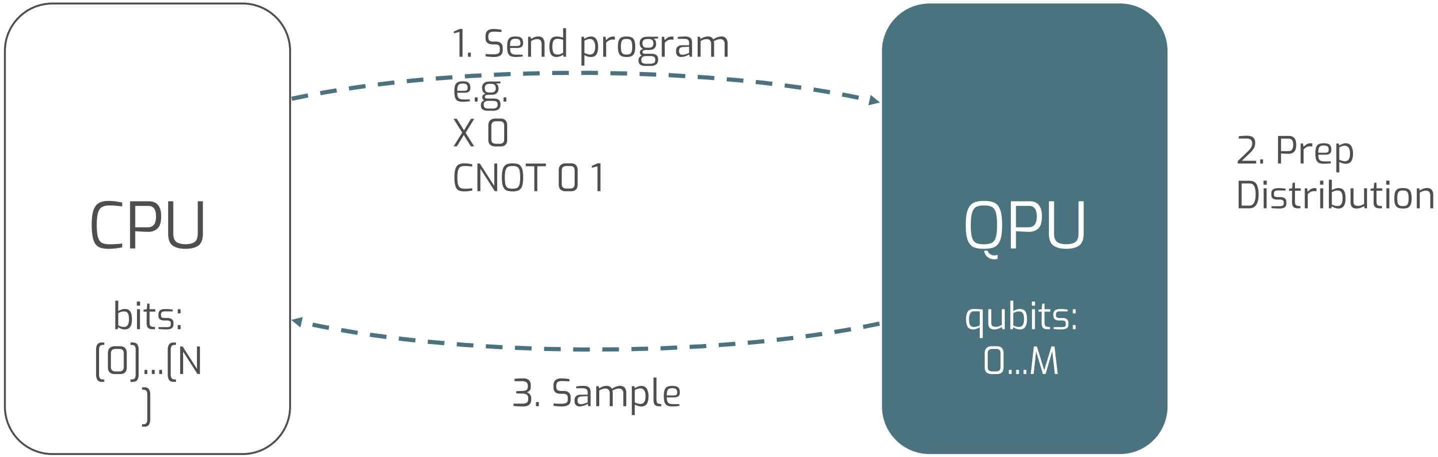


Forest is optimized for this with the Quil [01⟩ instruction set.

http://forest.rigetti.com
Smith, Curtis, Zeng. "A Practical Quantum Instruction Set Architecture" arXiv:1608.03355

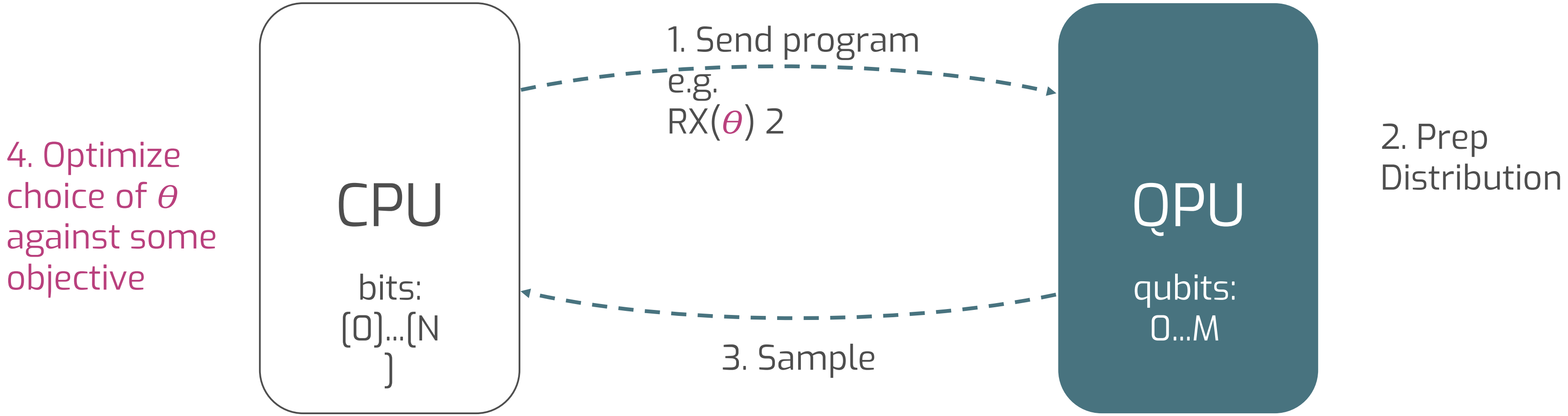
Useful quantum computation is **hybrid**

Quantum programming is preparing and sampling from complicated distributions



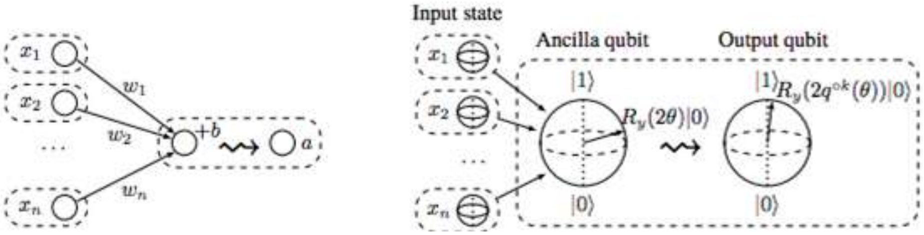
Useful quantum computation is **hybrid**

By parameterizing quantum programs we can train them to be robust to noise



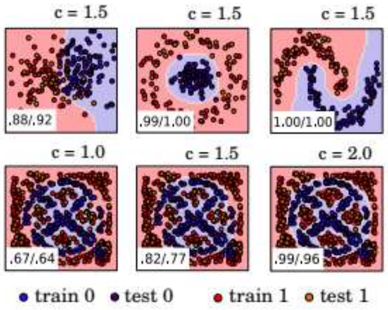
Quantum Machine Learning

> Quantum neuron: an elementary building block for machine learning on quantum computers. (Cao et al. 2017)

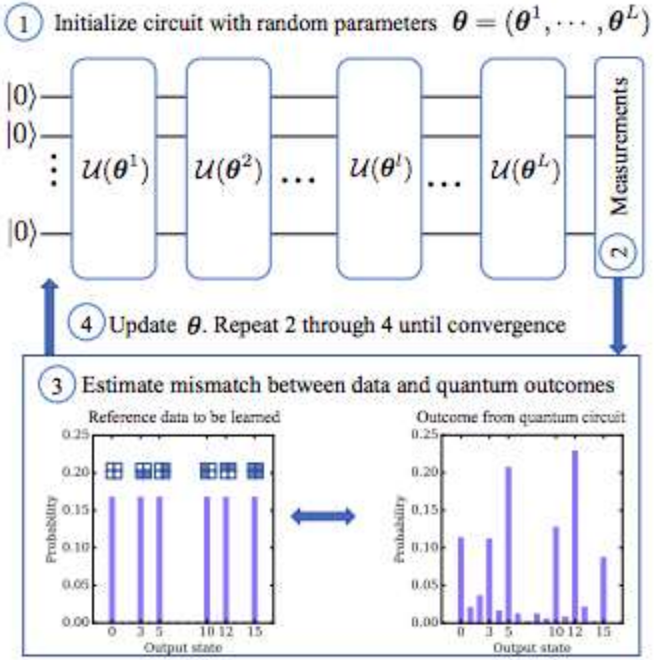


> Quantum circuit learning. (Mitarai et al. 2018)

> Quantum machine learning in feature Hilbert spaces. (Schuld and Killoran 2018)



A generative modeling approach for benchmarking and training shallow quantum circuits. (Benedetti et al. 2018)



The Variational Quantum Eigensolver

Used for the electronic structure problem in quantum chemistry

1. MOLECULAR DESCRIPTION

e.g. Electronic Structure Hamiltonian

$$H = \sum_{i,j<i}^{N_n} \frac{Z_i Z_j}{|R_i - R_j|} + \sum_{i=1}^{N_e} \frac{-\nabla_{r_i}^2}{2} - \sum_{ij}^{N_n, N_e} \frac{Z_i}{|R_i - r_j|} + \sum_{i,j<i}^{N_e} \frac{1}{|r_i - r_j|}.$$

2. MAP TO QUBIT REPRESENTATION

e.g. Bravyi-Kitaev or Jordan-Wigner Transform

e.g. DI-HYDROGEN

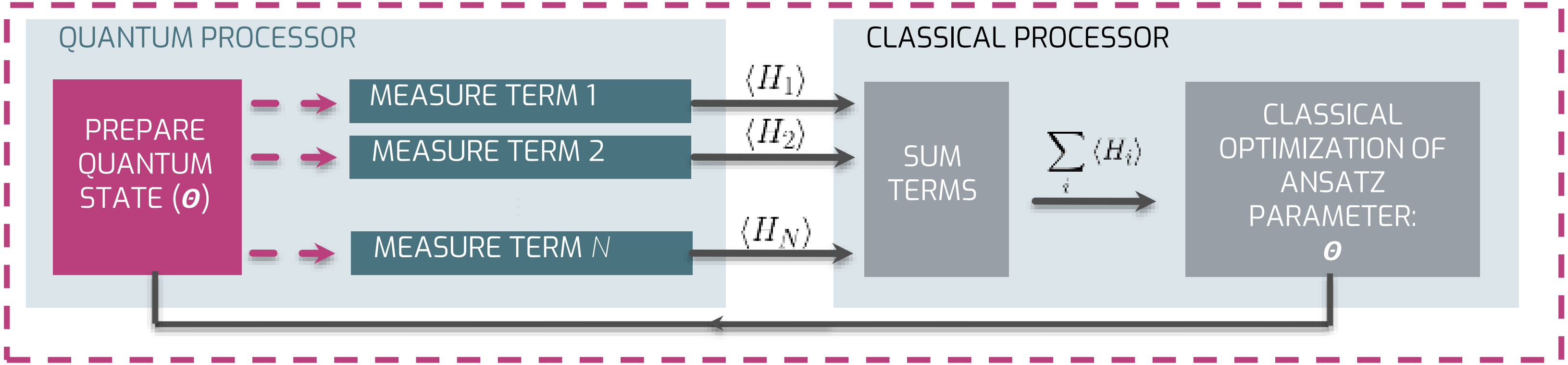
$$\begin{aligned} H = {} & f_0 \mathbb{1} + f_1 Z_0 + f_2 Z_1 + f_3 Z_2 + f_1 Z_0 Z_1 \\ & + f_4 Z_0 Z_2 + f_5 Z_1 Z_3 + f_6 X_0 Z_1 X_2 + f_6 Y_0 Z_1 Y_2 \\ & + f_7 Z_0 Z_1 Z_2 + f_4 Z_0 Z_2 Z_3 + f_3 Z_1 Z_2 Z_3 \\ & + f_6 X_0 Z_1 X_2 Z_3 + f_6 Y_0 Z_1 Y_2 Z_3 + f_7 Z_0 Z_1 Z_2 Z_3 \end{aligned}$$

3. PARAMETERIZED ANSATZ

e.g. Unitary Coupled Cluster
Variational Adiabatic Ansatz

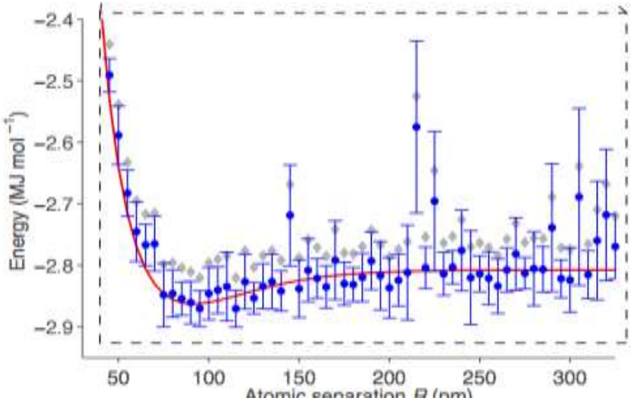
$$\frac{\langle \varphi(\vec{\theta}) | \, H \, | \varphi(\vec{\theta}) \rangle}{\langle \varphi(\vec{\theta}) | \varphi(\vec{\theta}) \rangle} \geq E_0$$

4. RUN Q.V.E. QUANTUM-CLASSICAL HYBRID ALGORITHM

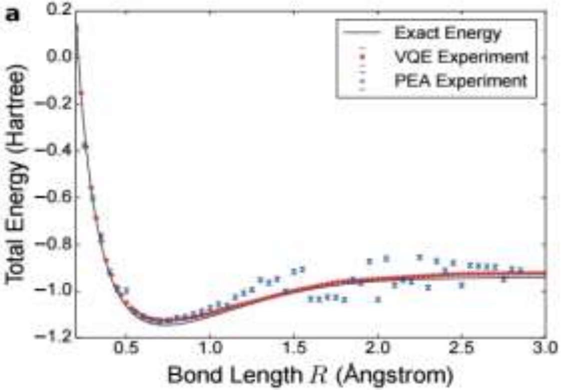


O'Malley, P. J. J., et al. (2015). Scalable Quantum Simulation of Molecular Energies. *arXiv:1512.06860*.
Wecker, D., et al. (2015). Progress towards practical quantum variational algorithms. *Physical Review A*, *92*(4), 042303.
McClean, J. R. et al. (2015). The theory of variational hybrid quantum-classical algorithms. *arXiv:1509.04279*.
Peruzzo, A., et al. (2014). A variational eigenvalue solver on a photonic quantum processor. *Nature communications*, *5*.

VQE Simulations on Quantum Hardware

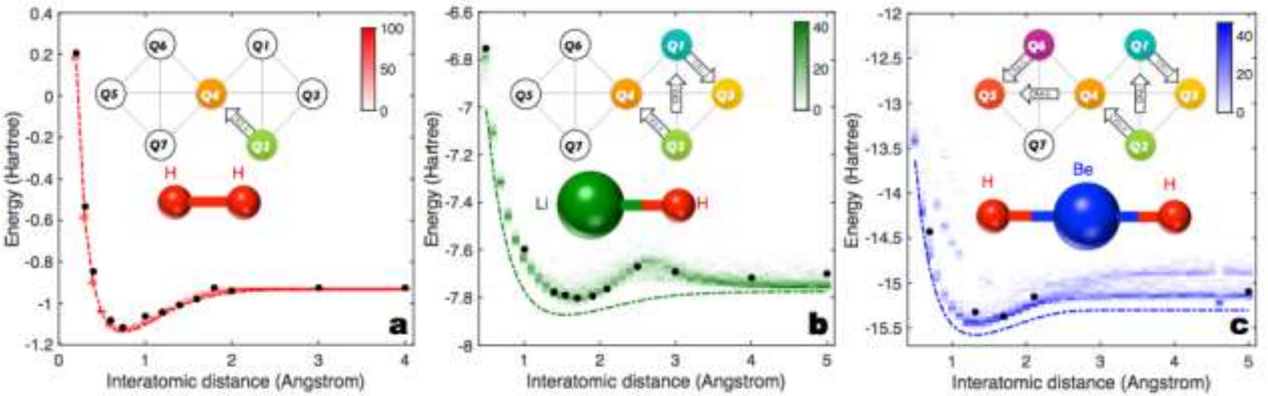


Peruzzo et al. 1304.3061



O'Malley et al. 1512.06860

Kandala et al.
1704.05018



Quantum Approximate Optimization Algorithm

(QAOA) Hybrid algorithm used for constraint satisfaction problems

Given binary constraints:

$$z \in \{0,1\}^n$$

$$C_a(z) = \begin{cases} 1 & \text{if } z \text{ satisfies the constraint } a \\ 0 & \text{if } z \text{ does not .} \end{cases}$$

MAXIMIZE

$$\boxed{C(z) = \sum_{a=1}^{m} C_a(z)}$$

Traveling Salesperson   Scheduling

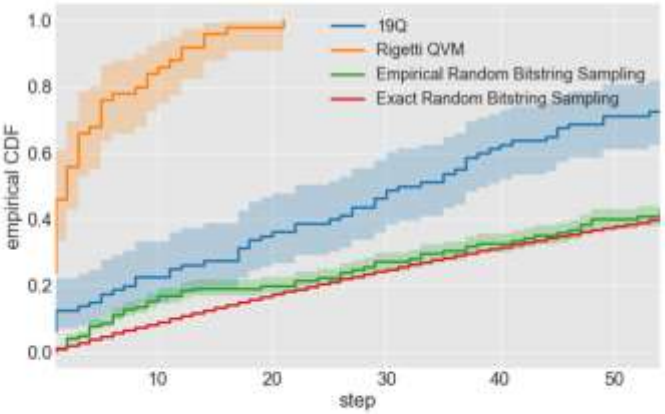
Hadfield et al. 2017 (1709.03489)

K-means clustering

Otterbach et al. 2017 (1712.05771)

Boltzmann Machine Training

Verdon et al. 2017 (1712.05304)



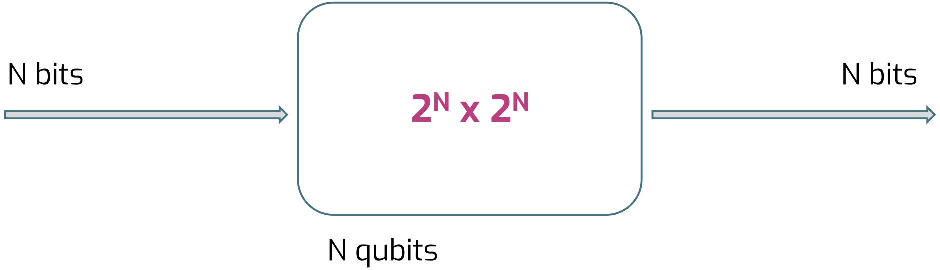
QAOA in **Forest**

In ***14*** lines of code

```
from pyquil.quil import Program
from pyquil.gates import H
from pyquil.paulis import sI, sX, sZ, exponentiate_commuting_pauli_sum
from pyquil.api import QPUConnection

graph = [(0, 1), (1, 2), (2, 3)]
nodes = range(4)

init_state_prog = sum([H(i) for i in nodes], Program())
h_cost = -0.5 * sum(sI(nodes[0]) - sZ(i) * sZ(j) for i, j in graph)
h_driver = -1. * sum(sX(i) for i in nodes)

def qaoa_ansatz(betas, gammas):
    return sum([exponentiate_commuting_pauli_sum(h_cost)(g) +
exponentiate_commuting_pauli_sum(h_driver)(b) \
        for g, b in zip(gammas, betas)], Program())

program = init_state_prog + qaoa_ansatz([0., 0.5], [0.75, 1.])

qvm = QPUConnection()
qvm.run_and_measure(program, qubits=nodes, trials=10)
```

What do near term applications look like?

The "big-memory small pipe" mental model for quantum computing



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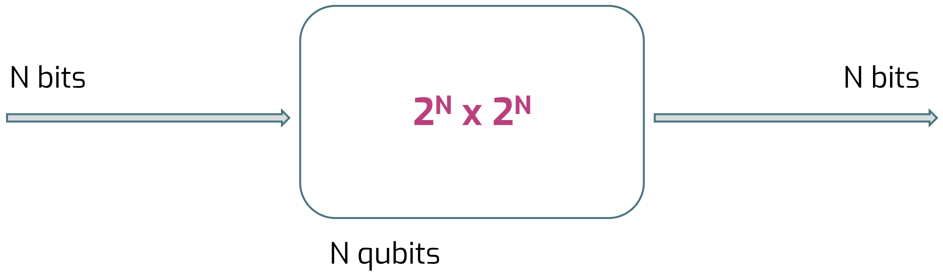


CRITERIA:

- Complex models (esp. If represented in a high dimensional vector space)
- Small data (QC has limited I/O)
- NOT real-time applications (again due to limited I/O)
- Approximate solutions are useful (indicates robustness to noise in early quantum processors)

Major Technology Challenges for Quantum Computing

> Existence of valuable robust applications with hundreds to thousands of qubits

> Reducing noise

> Integrating chip design, fabrication, control systems, software

> Implementing quantum error correction

Upcoming technology milestones

1. Quantum computers exist (Today)

1. Quantum supremacy (18-24 mos)
   not as big a deal as it sounds, but still a bit deal

1. Limited quantum advantage (3-5 years)

1. Broad quantum advantage (5+ years)

Rampant Discussion #1

Part 2. The Industry

What is the quantum industry and what is its trajectory?

What is the customer landscape?

How do I get involved as a

{scientist, programmer, entrepreneur,

investor}?

The emerging quantum landscape has a taxonomy

General-purpose ("Gate-based") quantum computing

Superconducting circuits

Commercial ← → *Academic*

- Semi-conductor tech
- Near "supremacy" scale

Topological systems

Photonic systems

Ion traps

- Good individual qubits
- Scalability not proven

Quantum software & consulting

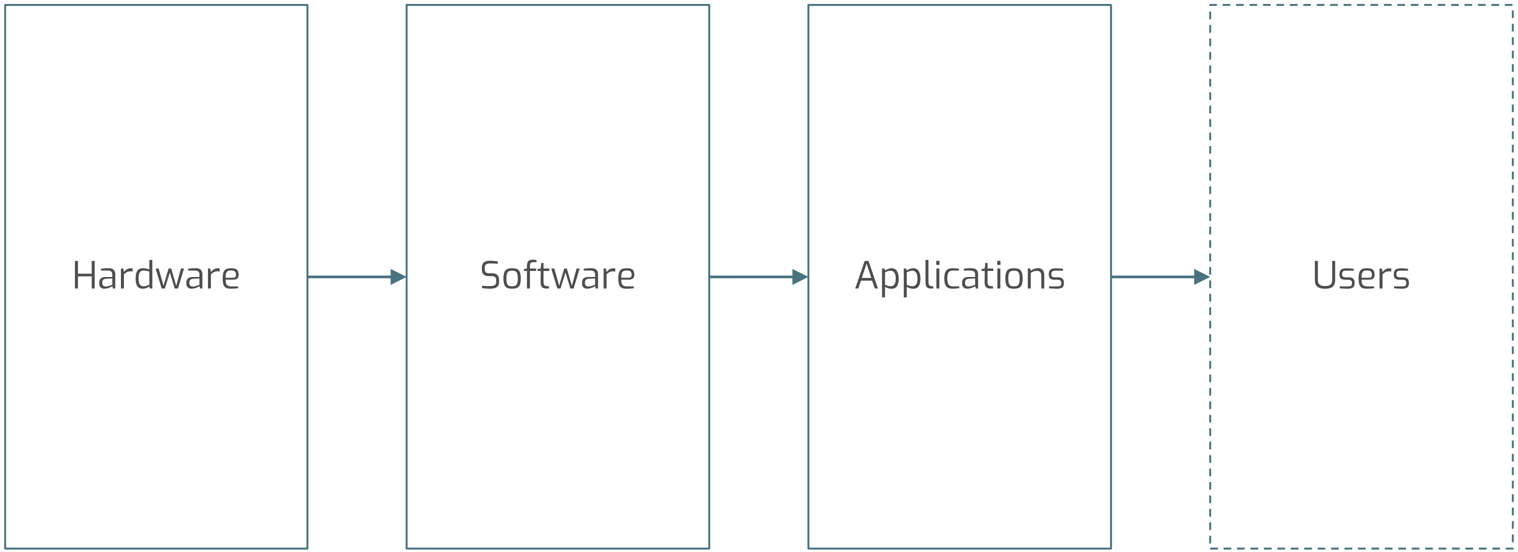
- Hardware agnostic
- Long-term apps
- Consulting / benchmarking services

Quantum annealing

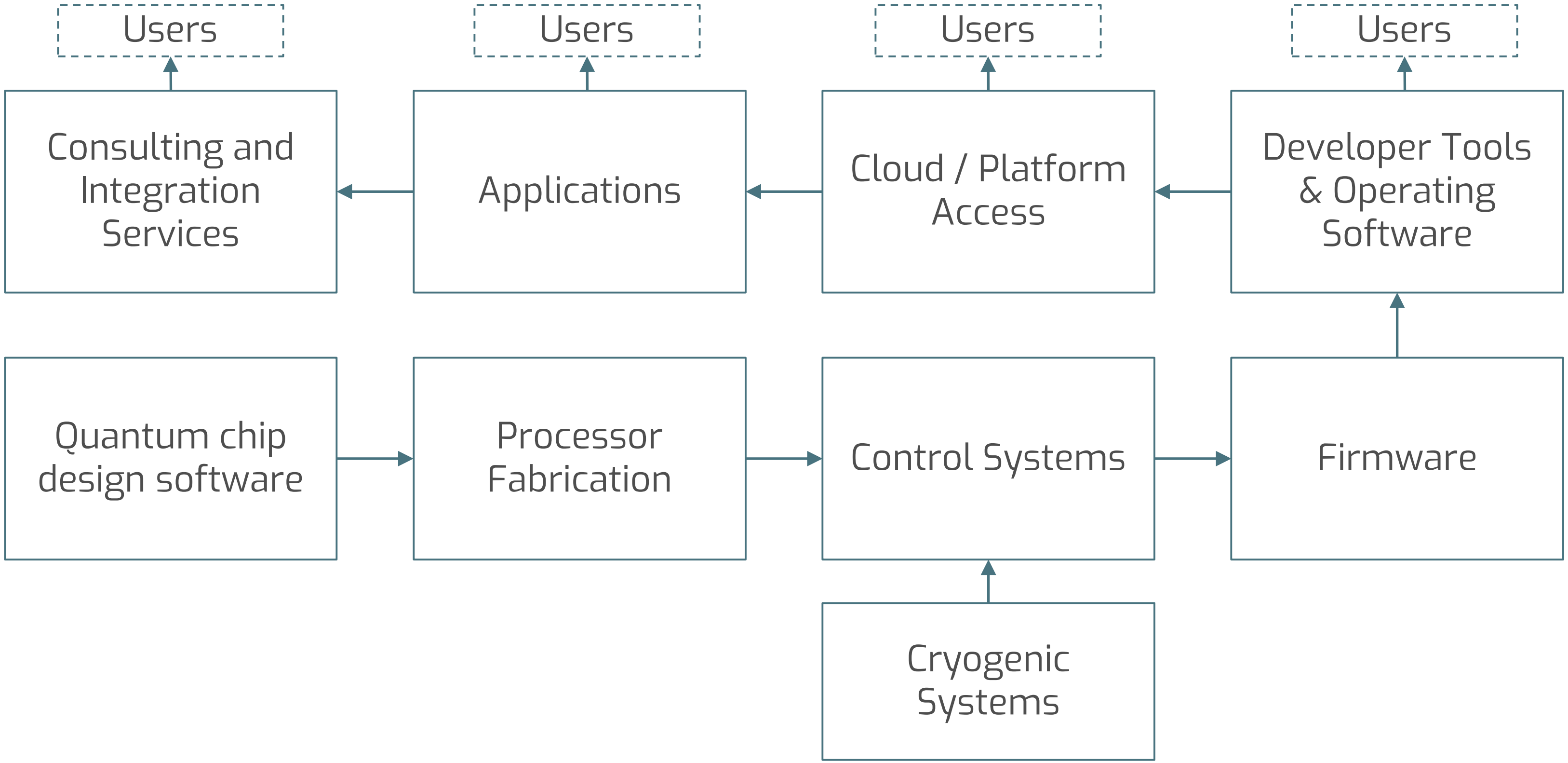
- Limited programmability
- Narrow applications

A full supply and demand side industry is emerging

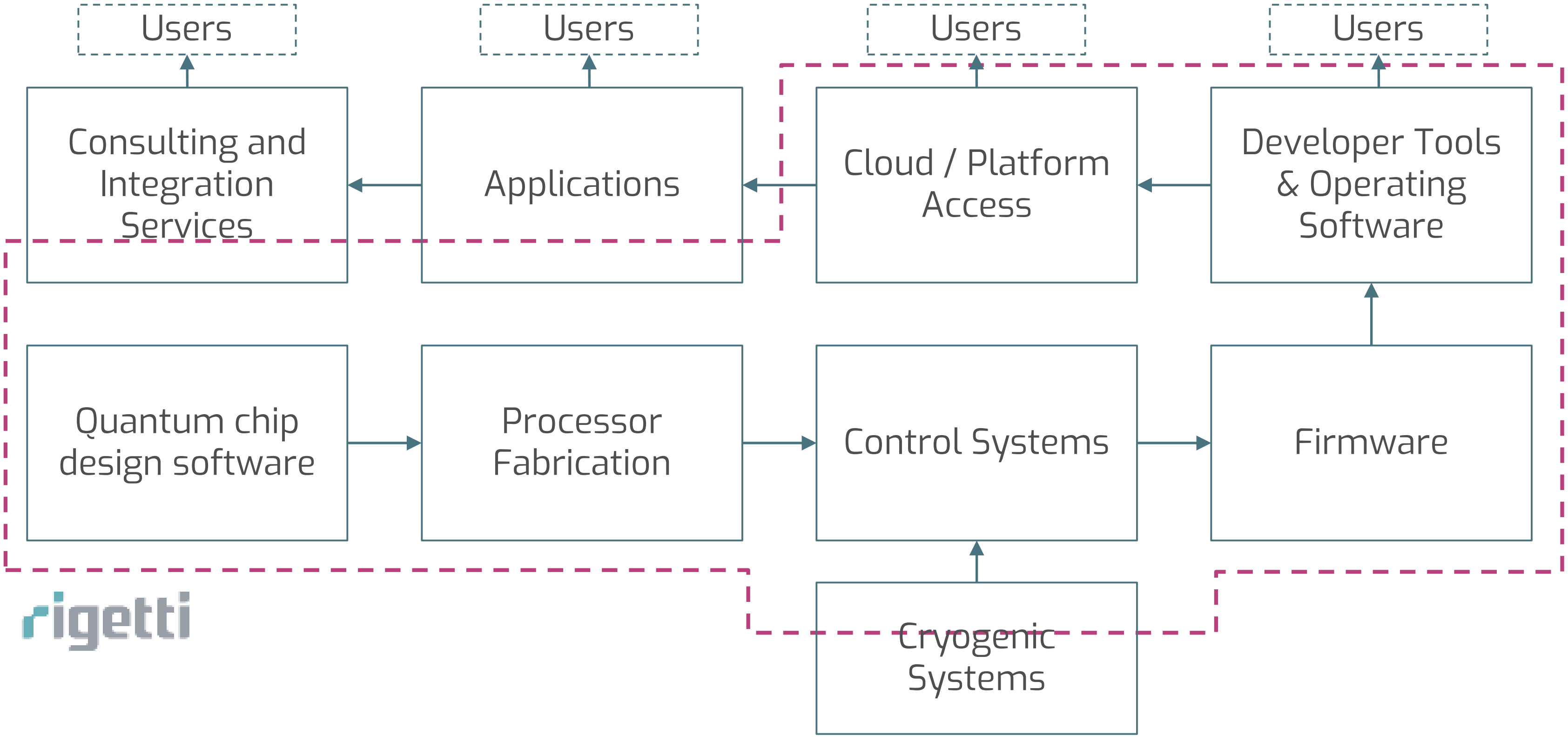
Lots of people have this unsophisticated and limited view:



The real picture ~~is~~ will eventually be a rich ecosystem

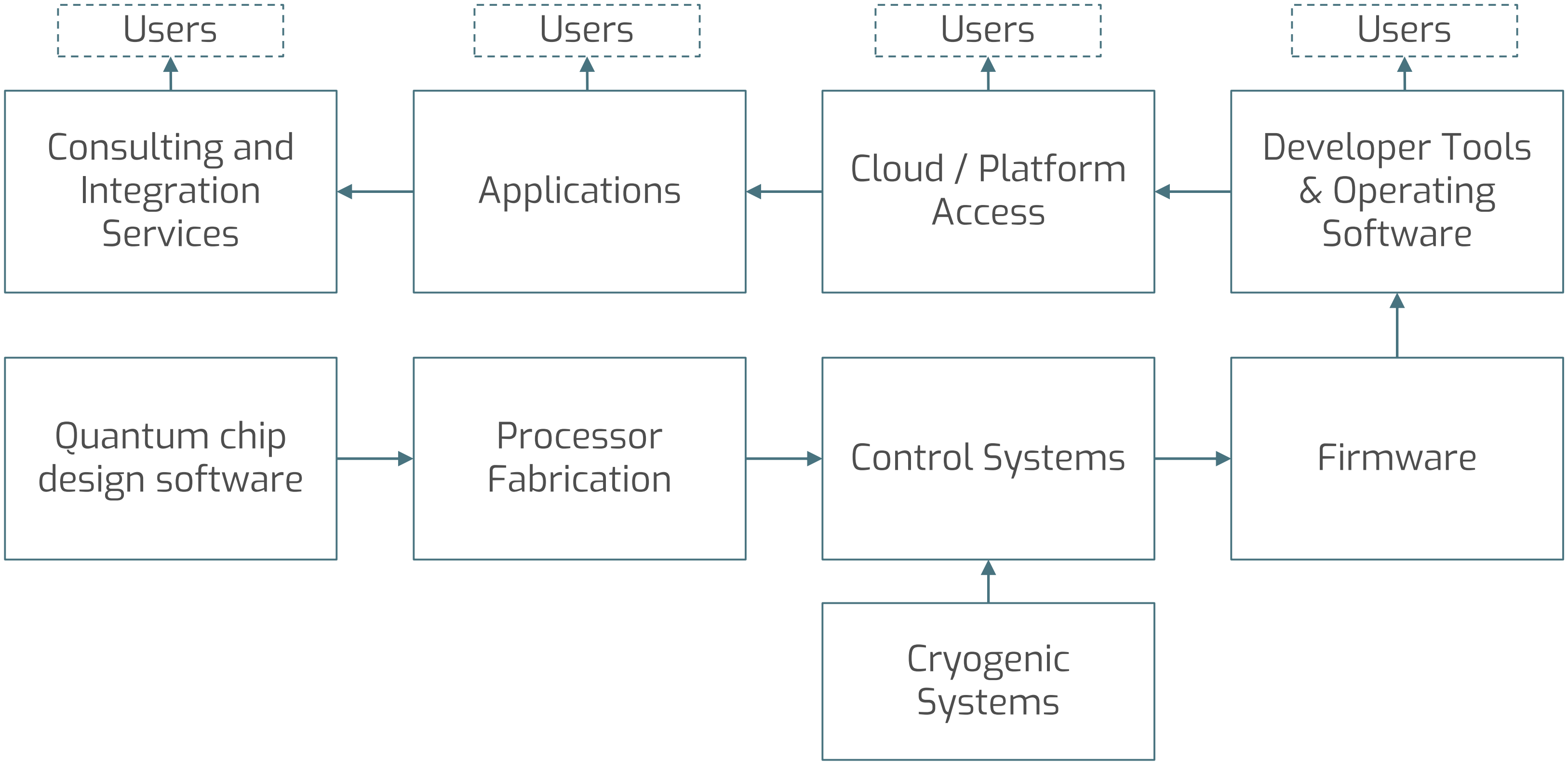


Rigetti has chosen to vertically integrate a lot in house

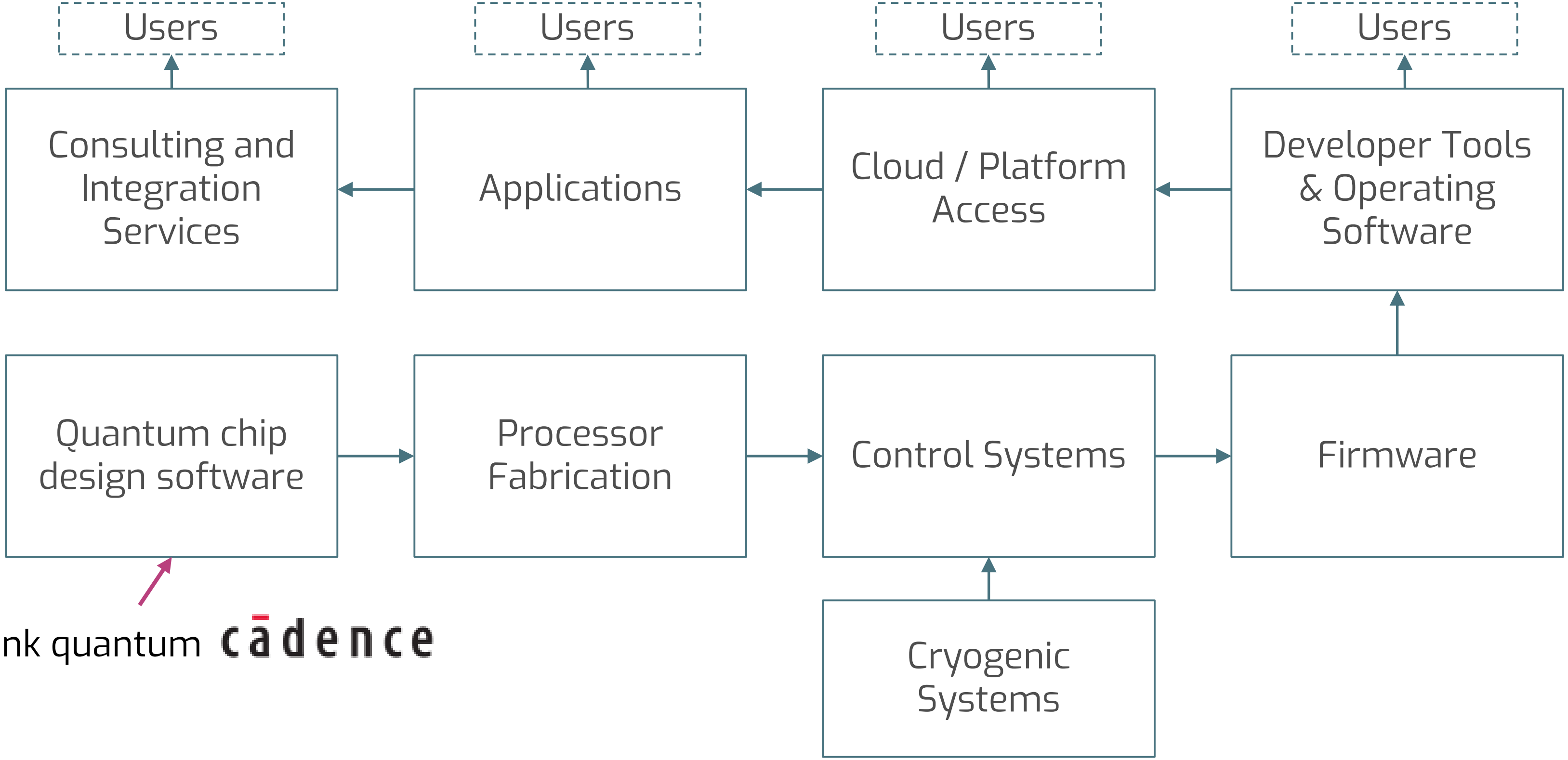


rigetti

There are startups and companies in every niche today

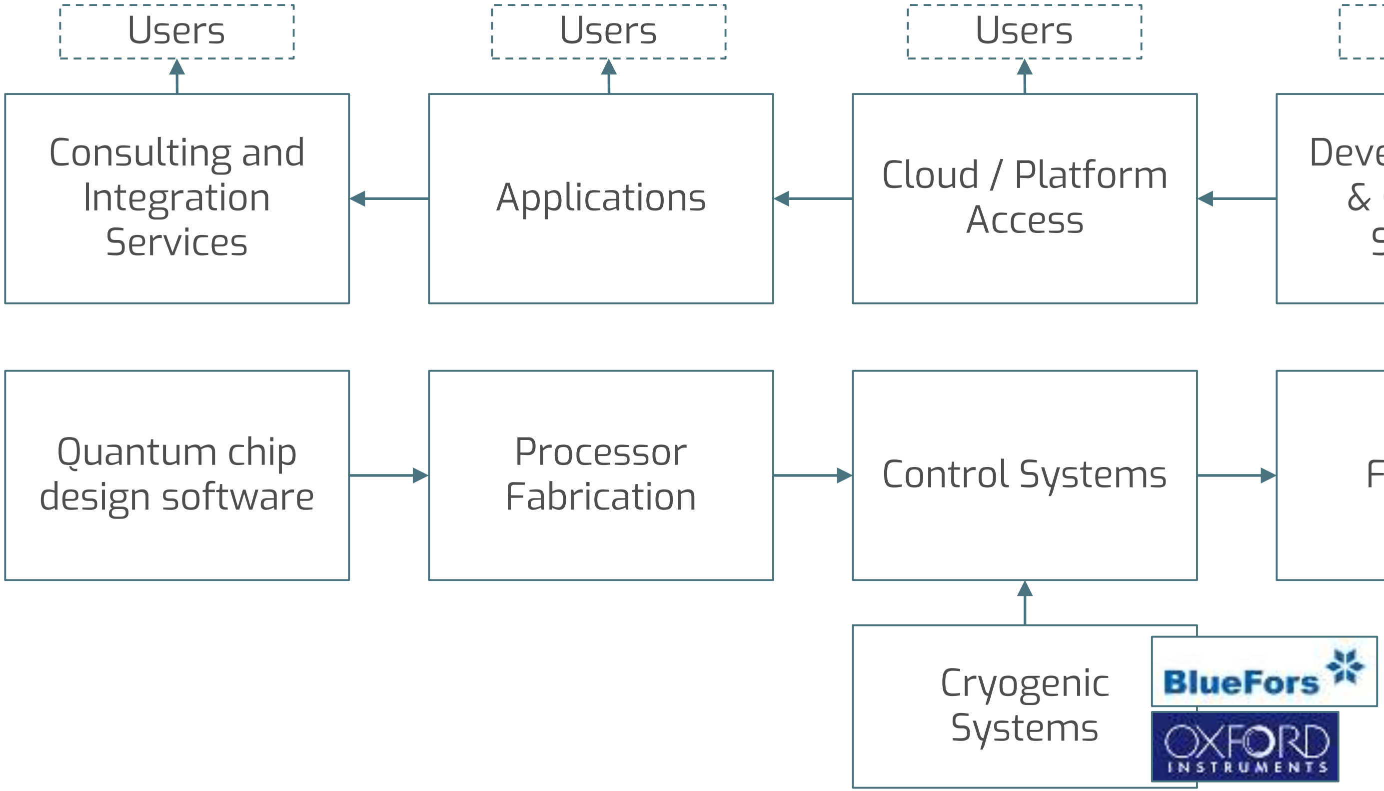


The classical analogs of each of these are massive



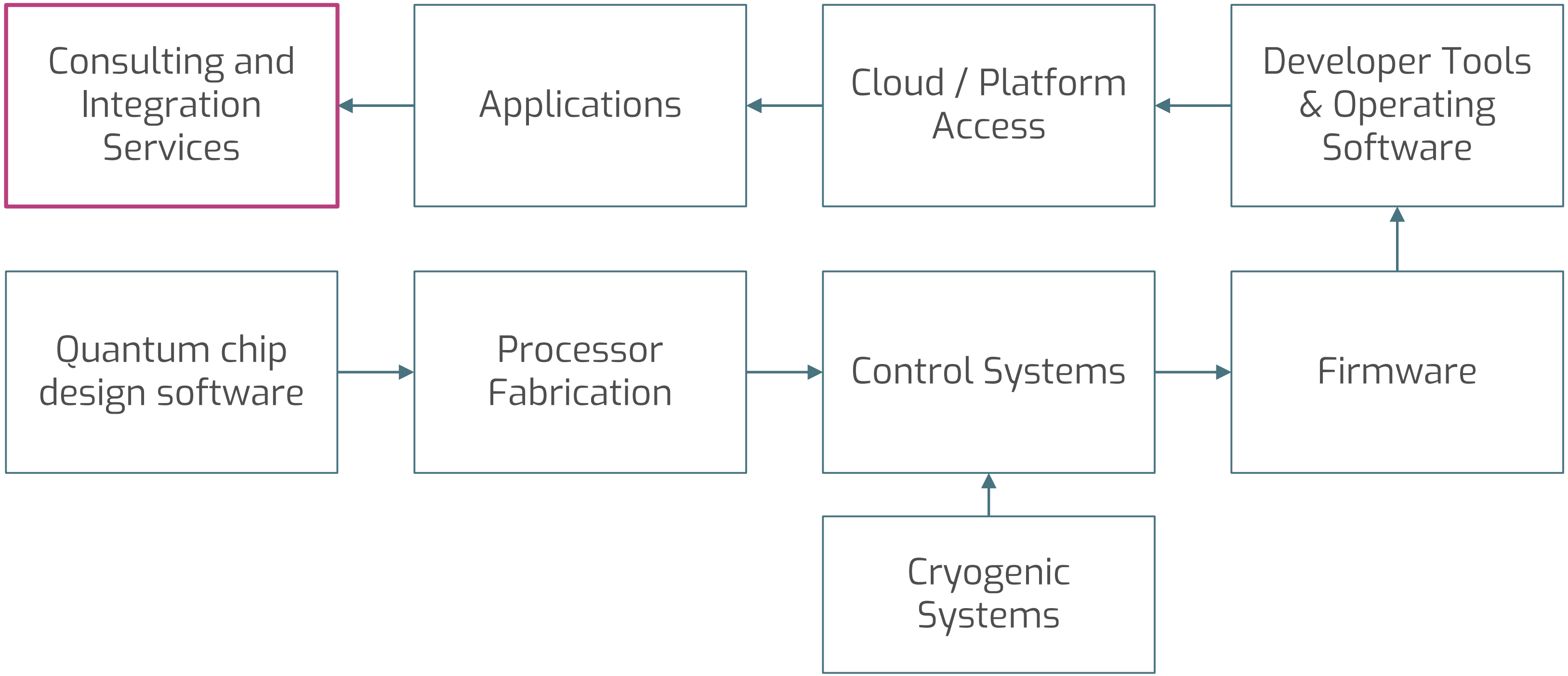
Think quantum cadence

Access to cryogenic systems is an exogenic risk to the field

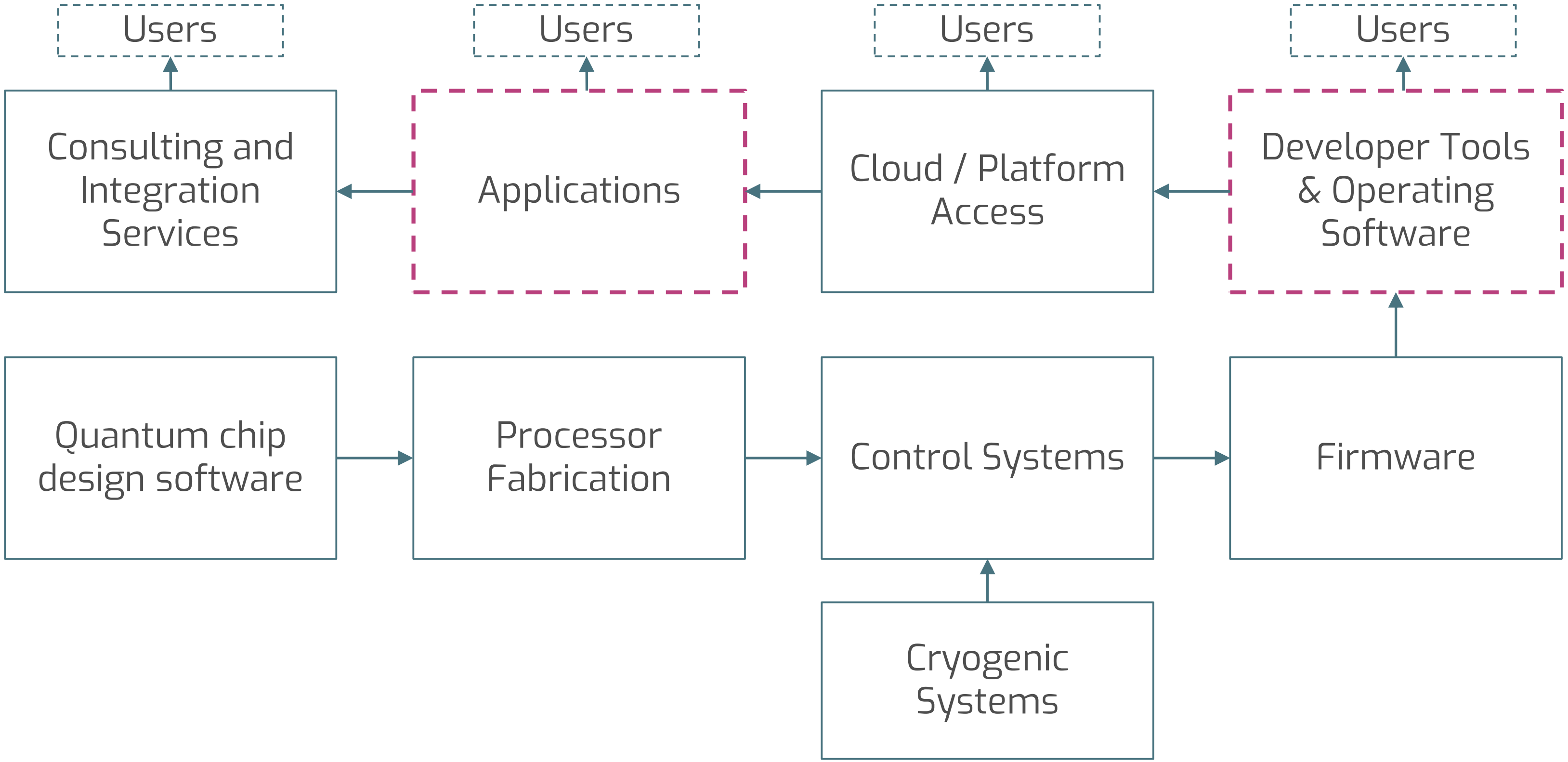


There is undifferentiated abundance & fragmentation at this part of the market

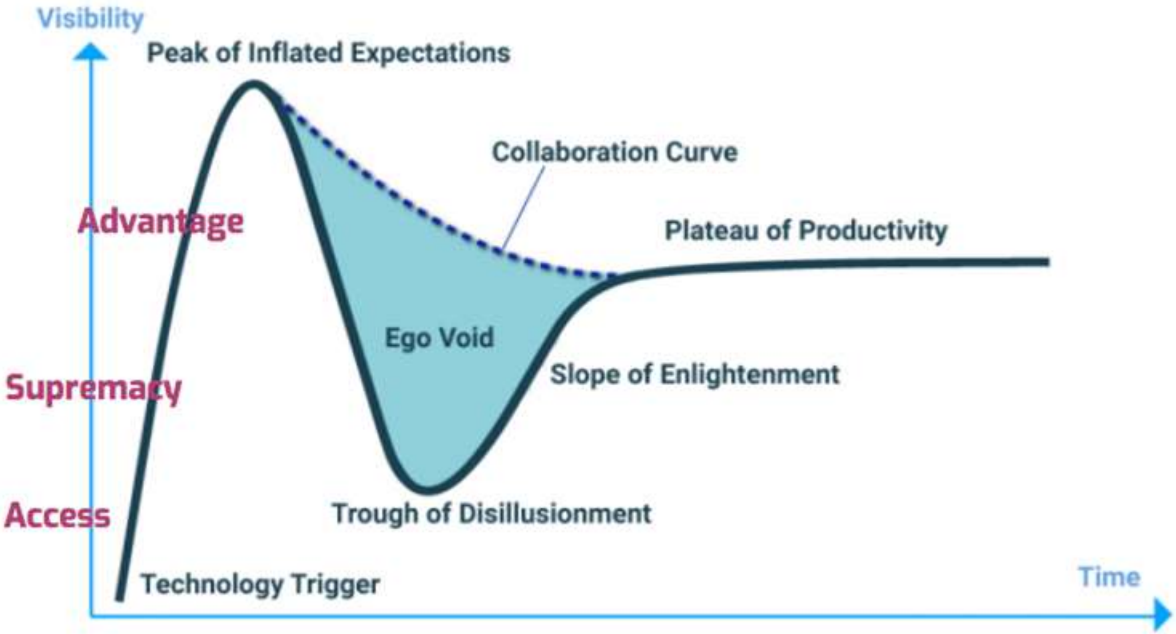
There are low barriers to entry



While nobody is seriously tackling other areas



Industry Trajectory: The Chasm



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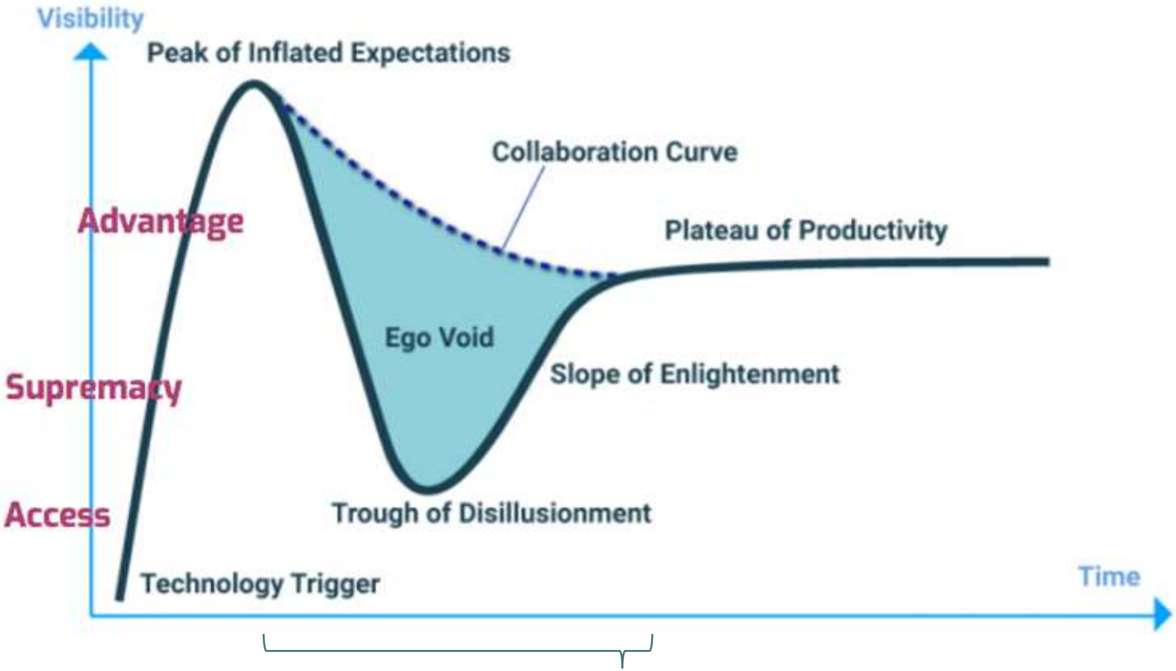

A combination of hardware, software, and applications are needed to cross this

Hardware is advancing but the software & apps ecosystem is fragmented

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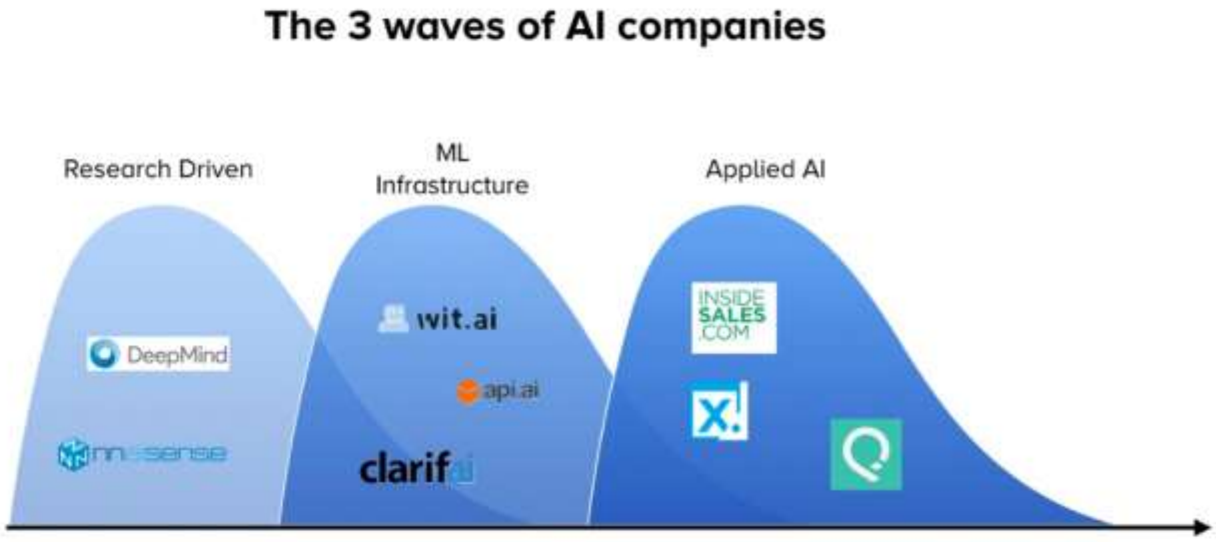
Will Quantum Software evolve analogously to AI? (acquisition heavy, no new great AI company)



Graphic from https://machinelearnings.co/winning-strategies-for-applied-ai-companies-f02cac0a6ad8

Government investment for chasm-crossing

Foreign governments have led the way with direct funding

- Australia Center of Excellence at UNSW
- Funded at **$25M** over 5yrs, 2016-2021

- Europe **€1B** over 5 years
- Individual countries also have initiatives,
  - Germany QUTEGA initiative likely **€300M** over 10yrs
  - UK made **£270M** investment in 2013

China has announced a **$10B**, four million square foot national quantum laboratory in Heifi devoted to quantum information sciences

Government investment for chasm-crossing

The US has led basic research and is starting to catch up on industry support

2019 DOE budget allocates **$105M** to quantum information science

- National Labs = primary recipients of this spend
- Exascale Computing Initiative $1.8 billion, some small portion of which will go to quantum

NSF's "Quantum Leap" initiative allocates **$30M** to quantum computing research initiatives, and another $30M to innovative HPC research

- Possible compute distribution to researchers via NSF grants

DARPA and the Army Research Lab have known spending of around **$30M** in quantum initiatives

Proposal requiring legislative action by Congress

- **$800M** over 5ys for civilian work + more on defense
- 3-6 QILabs to be built out, focused on hardware innovation
- QCAP (QC Access Program) is envisioned to allow gov't purchase of commercial quantum compute resources → at least **$100m** over 5ys

How to get involved as a scientist or programmer?

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> Join a company! Lots of roles for non-quantum non-PhD's!

will@rigetti.com

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> Do some programming and join the community!

github.com/rigetticomputing

[IBM] github.com/QISKit

http://forest.rigetti.com

http://www.qiskit.org

Bay Area Quantum Computing Meetup

meetup.com/Bay-Area-Quantum-Computing-Meetup

Quantum programming discussions

slack.rigetti.com

quantumcomputing.stackexchange.com

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For quantum to change the world we must cross a market chasm

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Will Zeng's unsolicited call for quantum startups in:

> Developer tools including optimizing compilers

> Application specific algorithms and software

> Other areas of the quantum industry stack

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Investors:

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- need more algorithms and applications focus towards advantage

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How to find & get focused teams out of academia and other fields and in position to invent the technologies that will take quantum through the chasm?

How to get involved as an entrepreneur or investor?

Have an idea? Come talk to me. I want to help.

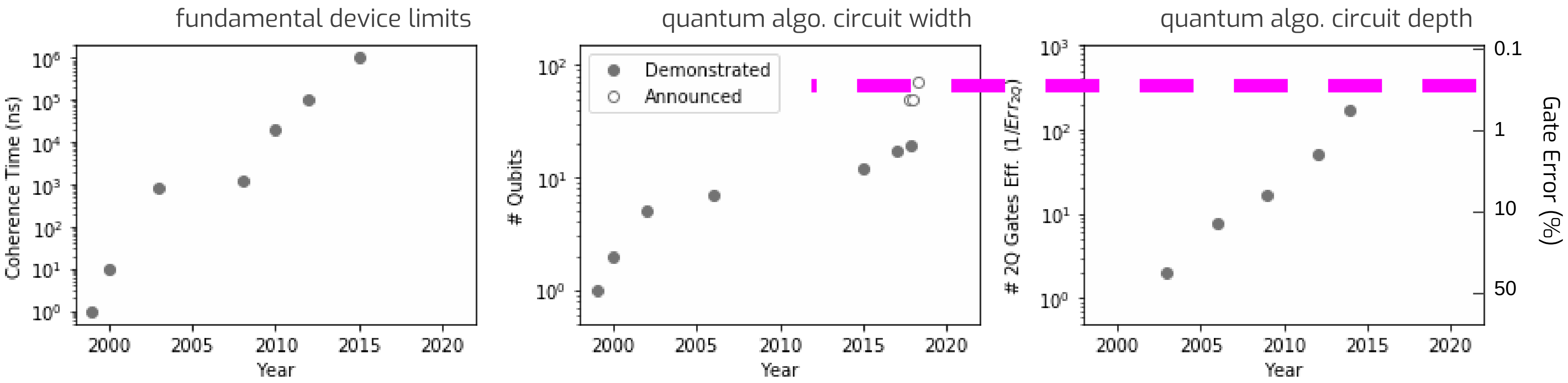
Rampant Discussion #2

How can we help this new industry change the world?

@wjzeng

Circuit QED

trends of the best results from nearly 20 years of SC qubits



adapted from Schoelkopf and Devoret
Science, 339, 6124 (2013)

"NISQ era" - Preskill
arXiv:1801.00862

adapted from Oliver, APS March 2018