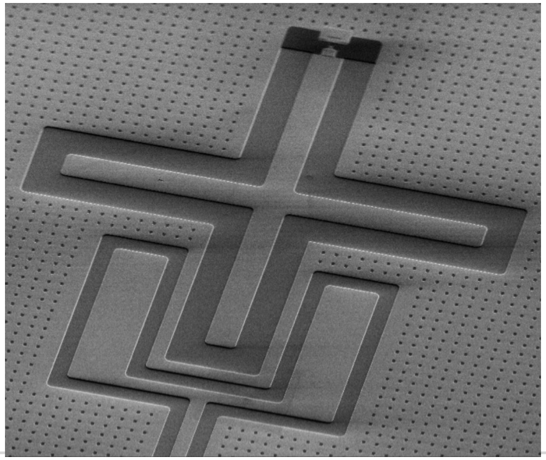
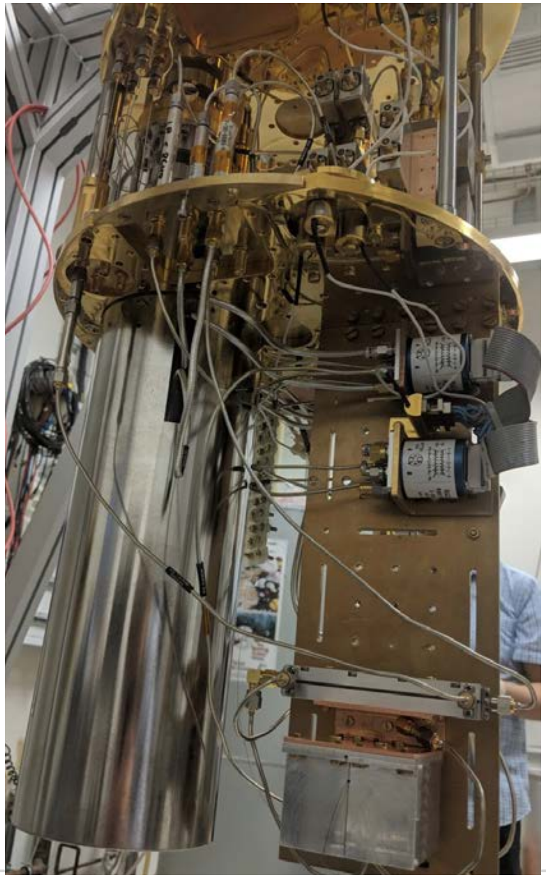
Quantum computers,
how do they work and what can they do?

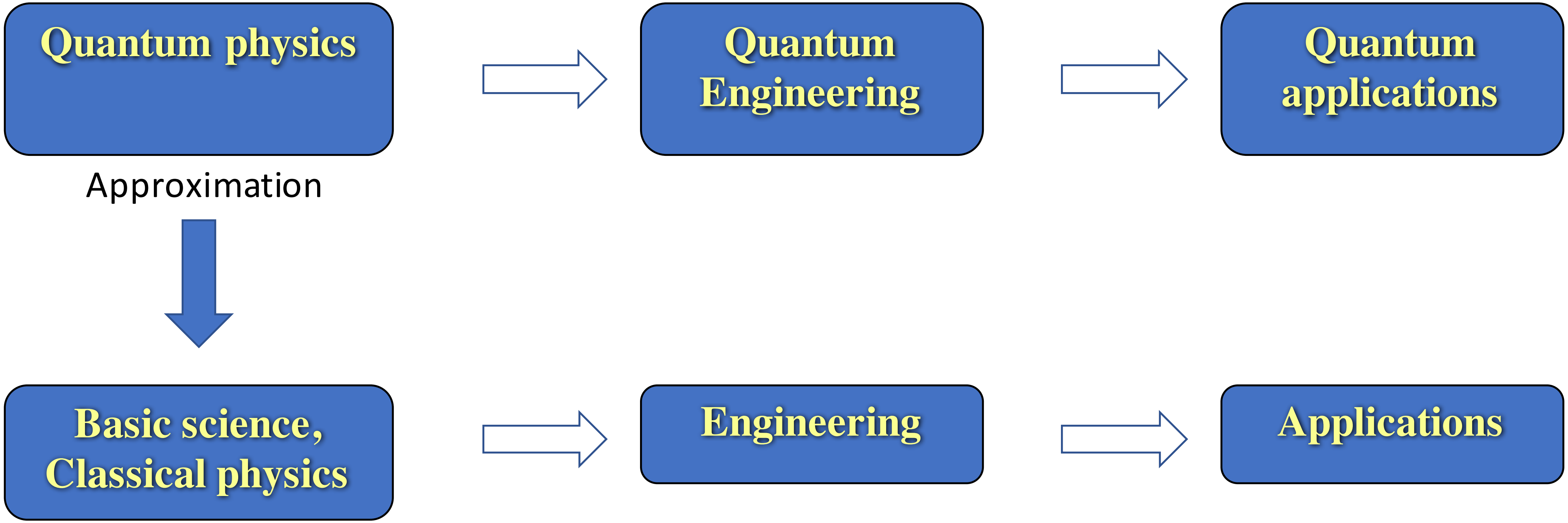
Outline

- Quantum technology
- Quantum computing
  - What is the advantage?
  - The qubits
  - Operating the quantum computer
- Quantum computing initiatives
- What to use quantum computing for?





Why Quantum Technology?



Quantum physics

Quantum Engineering

Quantum applications

Approximation

Basic science, Classical physics

Engineering

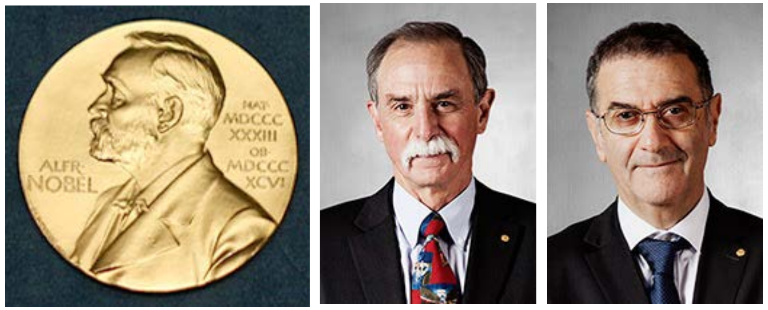
Applications

IT, Electronics,
Mechanics,
Chemistry, Energy

The Quantum Revolutions

The **first quantum revolution** resulted in:
The transistor and the Laser

The second quantum revolution
was pioneered by people like Haroche and Wineland achieving full control over individual quantum systems.



Serge Haroche and David Wineland were awarded the 2012 Nobel prize in physics for the ability to control quantum systems accurately.

If we use a quantum system to encode information we call them qubits

Quantum Technology
aims a exploiting the elements of the second quantum revolution:

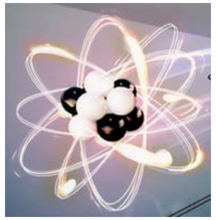
Superposition
Entanglement
Squeezing…

The four pillars of Quantum Technology

Four different sub-areas with different levels of maturity:

Quantum communication	**Quantum sensors**	**Quantum simulation**	**Quantum computing**
transmitting inherently secure messages	improving measurement technology	of complicated processes, otherwise too hard to simulate	solving problems much faster than ordinary computers
Already commercial	Short-term goal	Medium-term goal	Long-term goal
Secure communication Money transfer Quantum Internet	Atomic clocks Quantum limited microwave amplifiers	New drugs and catalysts Improving fertilizers Designing new materials	Optimization Machine learning Code breaking

Exploiting Superposition

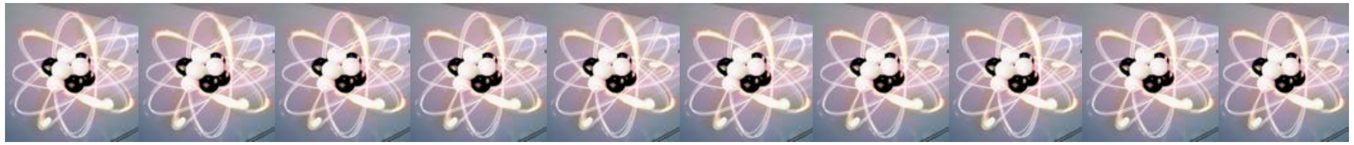


Superposition

A quantum bit (qubit) can represent two values at the same time: 0 and 1

Two qubits can represent 4 different numbers
Four qubits can represent 16 different numbers, and so on…

A register of *N* qubits can represent 2^N different states **simultaneously**



EXAMPLE: A register with 300 qubits can represent $2^{300} \approx 10^{100}$ states – more than the number of particles in the universe

Making an operation on 300 qubits corresponds to making a calculation on 10^{100} numbers simultaneously

=> MASSIVE PARALLELLISM!

An N qubit register can represent 2^N numbers

$2^1=2$

$2^{10}=1024$

$2^{20}\sim 1$ million

60 qubits hard to simulate on todays supercomputer

300 qubits: $2^{300}\sim 10^{100}\sim$more than particles in the universe

The first useful quantum algorithm

1994 Peter Shor demonstrates a quantum computer algorithm to find factors of large numbers

1789 x 1801 = 3221989	Easy
3221989 = ? x ?	Hard (RSA-hard)

The asymmetry is used to encode information, used in https

1996 Peter Shor shows that error correction of qubits is possible

Peter Shor
1994 Bell Labs
Now MIT

This started the interest in quantum computing

Performance of a quantum computer

- Number of qubits
    - Todays best operating quantum computer has 15-20 qubits
- Lifetime of (the worst) qubit
    - Depends on implementation
    - Can be prolonged by error correction
- Speed of qubit gates
    - Single qubit gates and two qubit gates

Ratio is important

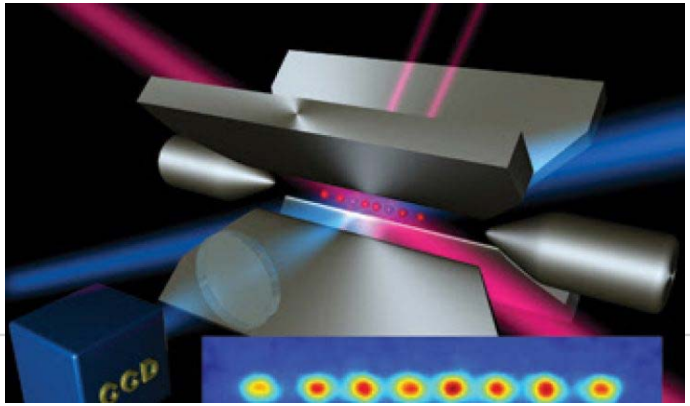
- Connectivity
    - How many other qubits can each qubit couple to
    - Ideally each it should be possible to couple any qubit to any other qubit

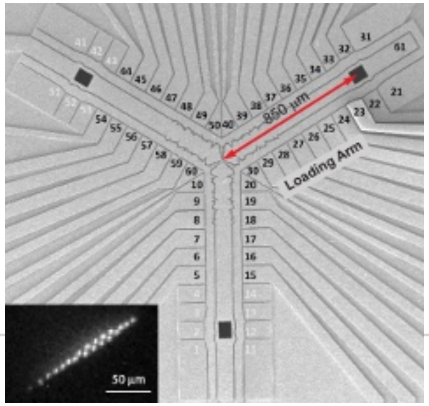
Physical implementations of qubits

Ion traps

+ Long lifetime
+ Good connectivity
- Harder to scale up
- Slow two qubit gates

- Manipulated by laser pulses

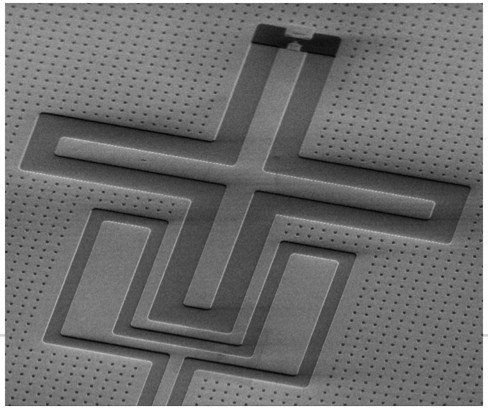


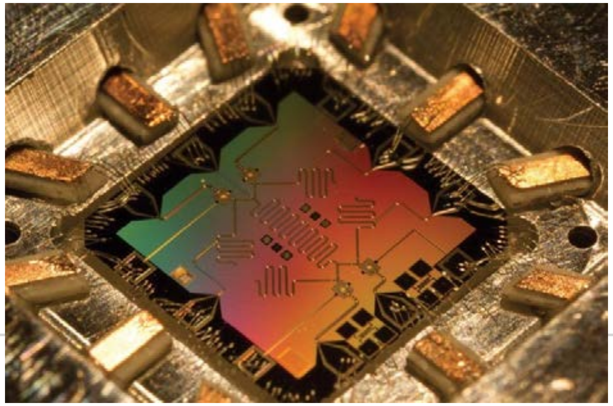


Superconducting qubits

+ Scalable
+ Fast gates
- Relatively short lifetime
- Full connectivity is harder

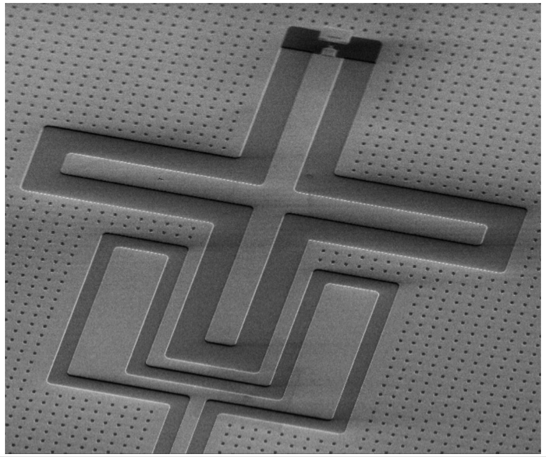
- Manipulated by microwave pulses

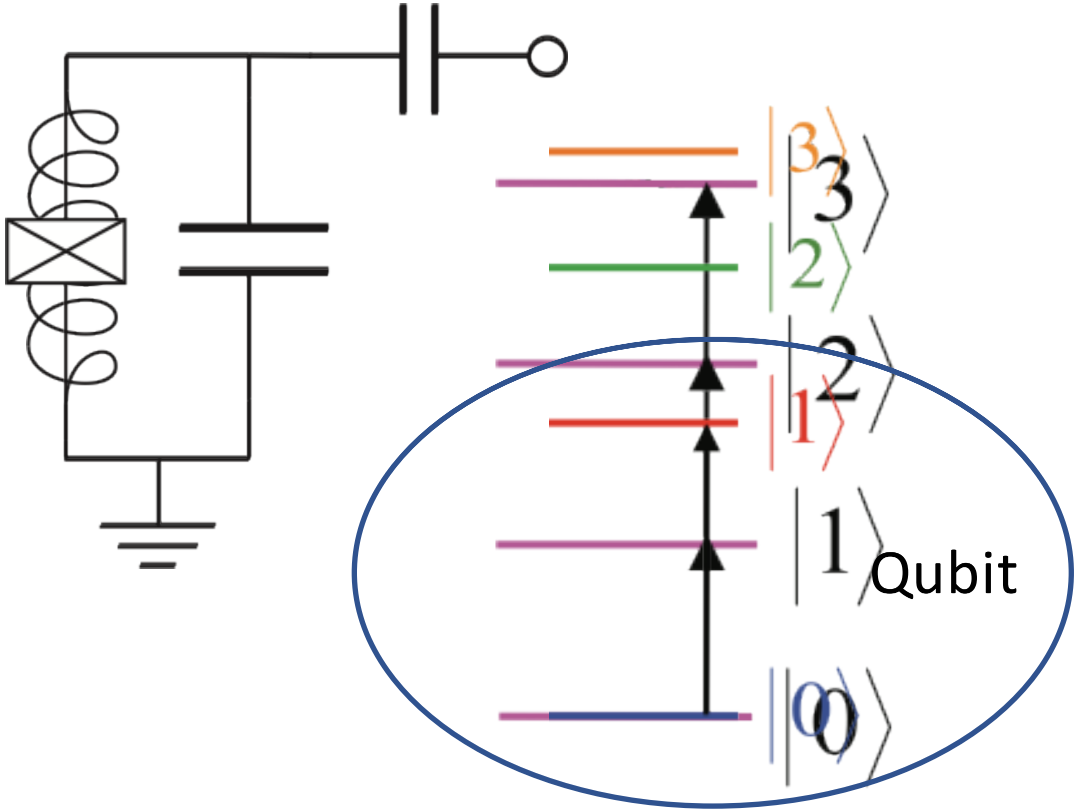




Superconducting qubits
Artificial atoms based on Josephson junctions

- Quantized electrical circuit
- Harmonic oscillator is not an atom
- Nonlinearity makes the circuit anharmonic and addressable
- Small JJ is a good nonlinear inductor



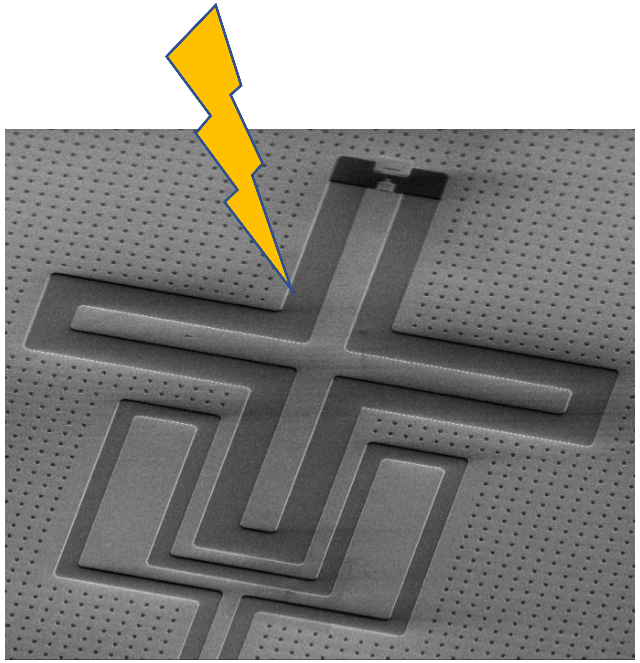


Koch *et al*. PRA (2007)

Protecting the qubit from its environment

- Interaction with the environment can cause decoherence; either **relaxation** or **dephasing**
- Decoherence is a bad thing and therefore the qubits needs to be in a cold and dark environment
- Decoherence limits the lifetime of the qubit
- This can be mitigated with error correction

Error correction is complicated by the noncloning theorem

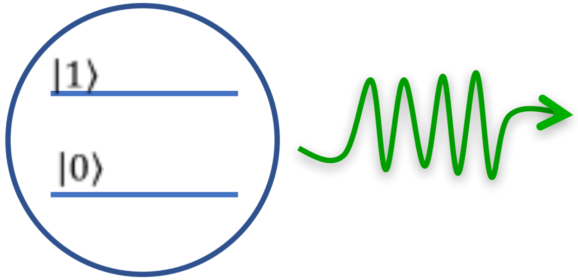


Decoherence

The decoherence determines the life time of the qubit

Relaxation

Spontaneous or stimulated emission

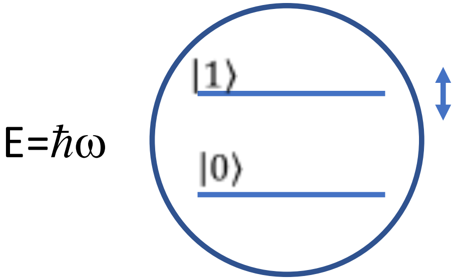


If the qubit losses energy we lose the information

Counter measures:
Cool the environment and decrease the coupling to the environment

Dephasing

Fluctuations of the atom frequency



The qubit acts like a clock. Dephasing is when the clock runs at the “wrong” speed
We do not know what the phase is.

Counter measures:
Make sure the frequency of the qubit is insensitive to its environment

How do you control the quantum computer

Problem to be solves

Describe the problem mathematically

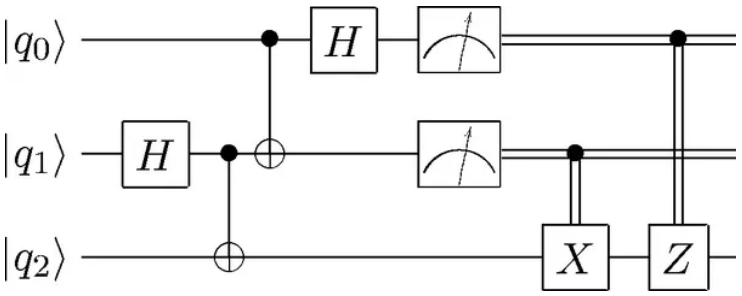
Mathematical description

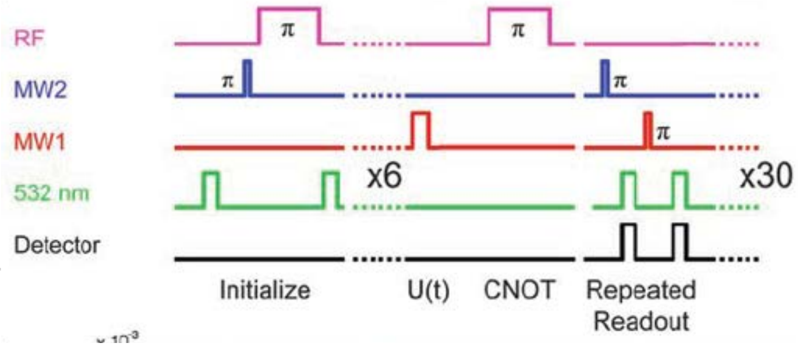
Convert to quantum gates and optimize number of needed gates

Quantum gates

Implement each gate into mw/laser pulses

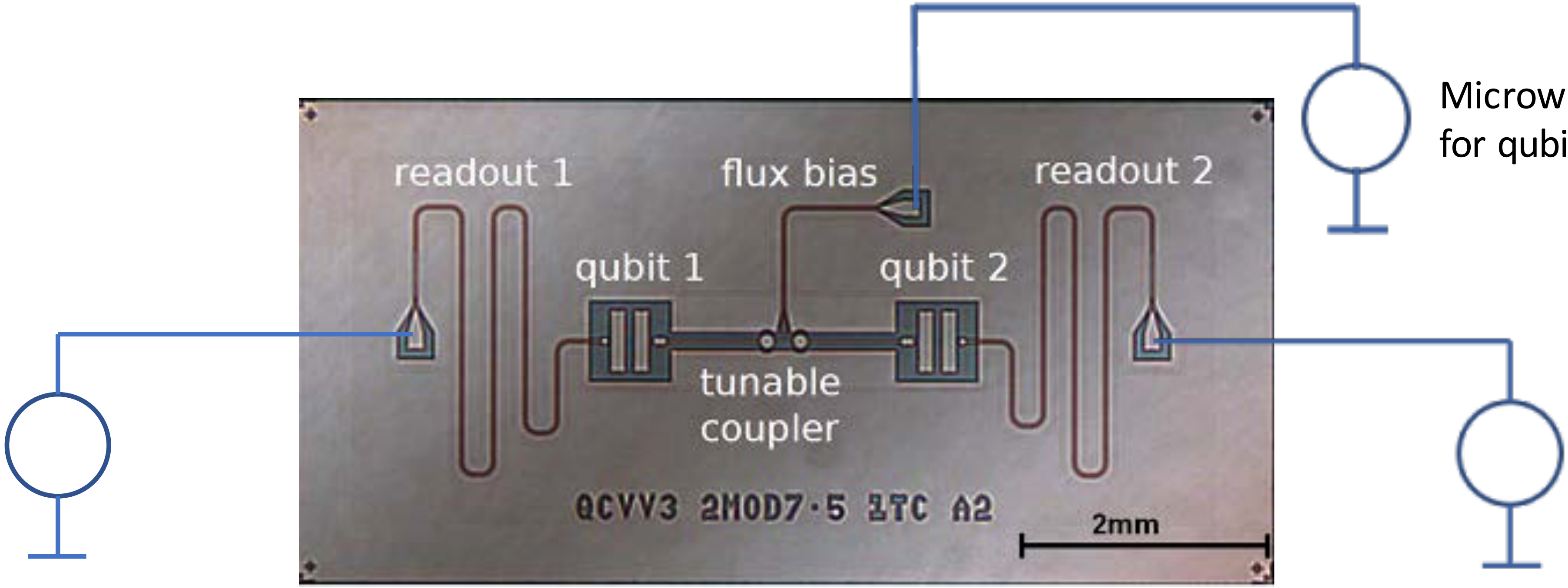
Microwave or laser pulses





How to operate a quantum computer

Operation of the qubits is done by sending microwave pulses to the quantum processor



Microwave source for qubit coupling

Microwave source single qubit gates and readout

Microwave source for single qubit gates and readout

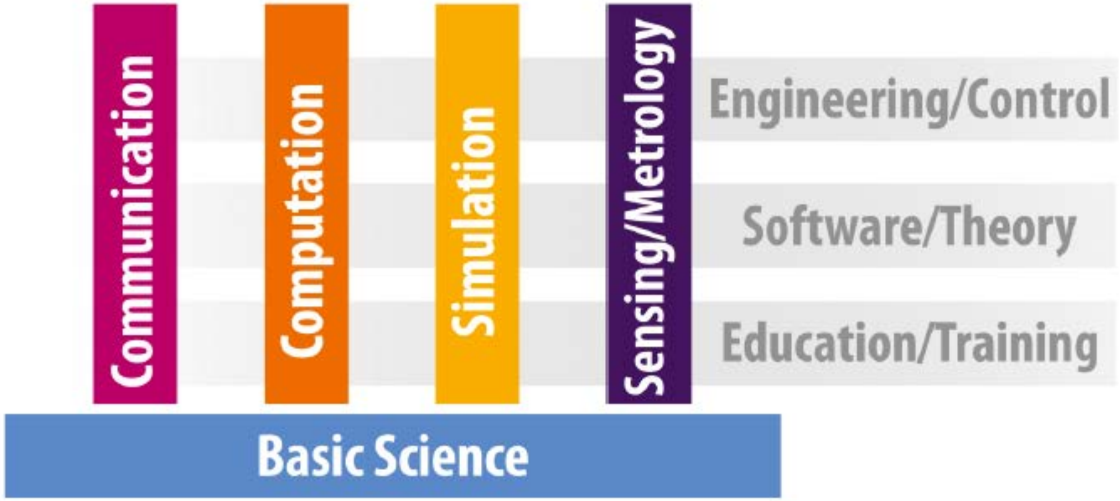
Wallraff group, ETH Zürich

Complications

Brut force: More than one laser or mw source per qubit
Stability and phase noise of the sources

EU Quantum Technology Flagship

Duration	10 years
EU	500 M€
Member states	500 M€
Start	Oct. 1, 2018



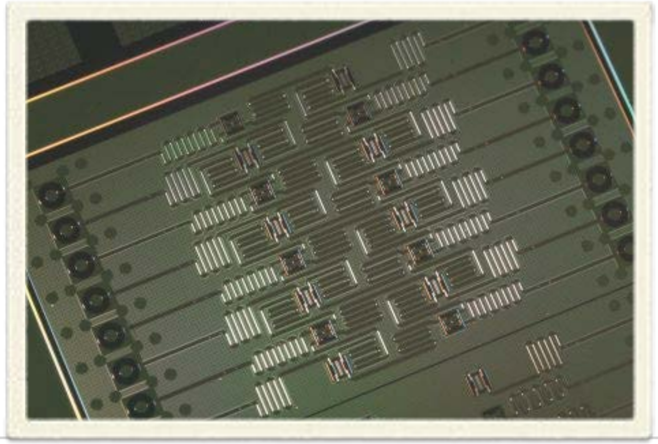
Two consortia have been funded to do quantum computing
OpenSuperQ and **AQTION**

Quantum computing – some recent news

Futurism news item, 23rd of June 2017, working on 49 qubit processor.
Now 72 (March 5 2018)

Future Society

Google is Closer Than Ever to a Quantum Computer Breakthrough



IBM Q

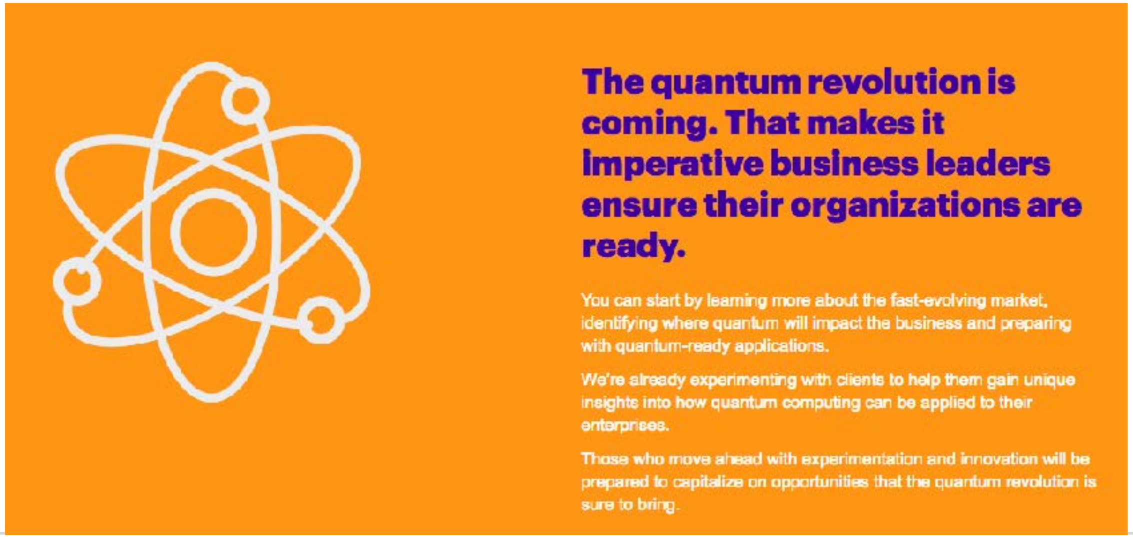
20 qubit online
50 qubit testing
10th of November 2017

$64 million start-up

rigetti

MIT Technology Review's
2017 list of 50 Smartest
Companies
June 27th 2017

Accenture:



The quantum revolution is coming. That makes it imperative business leaders ensure their organizations are ready.

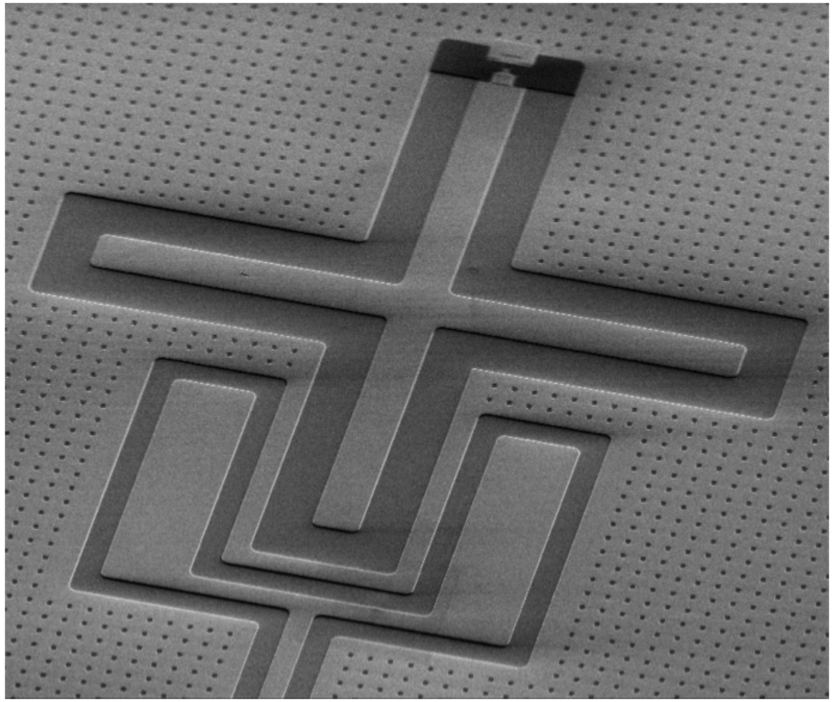
You can start by learning more about the fast-evolving market, identifying where quantum will impact the business and preparing with quantum-ready applications.

We're already experimenting with clients to help them gain unique insights into how quantum computing can be applied to their enterprises.

Those who move ahead with experimentation and innovation will be prepared to capitalize on opportunities that the quantum revolution is sure to bring.

Wallenberg Center for Quantum Technology

Main goals	i) To build a broad competence base in Sweden for Quantum Technology ii) To build a quantum computer based on superconducting circuits
Two parts	Core project on quantum computing Excellence program including all of Quantum Technology
Main location:	Chalmers
Including:	KTH, Lund (SU and LiU)
Duration:	10 years, (3+4+3 years) started 1/1 2018
Involving industry	SME for enabling technology Big industry for applications
Funding:	600 MSEK + 200 MSEK + ~150 MSEK KAW Universities Industry partners Quantum technology flagship: OpenSuperQ

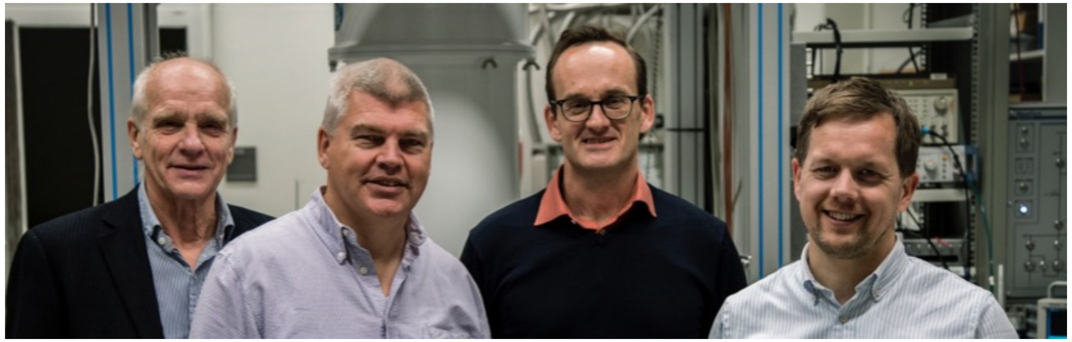


The Core project: building a quantum computer

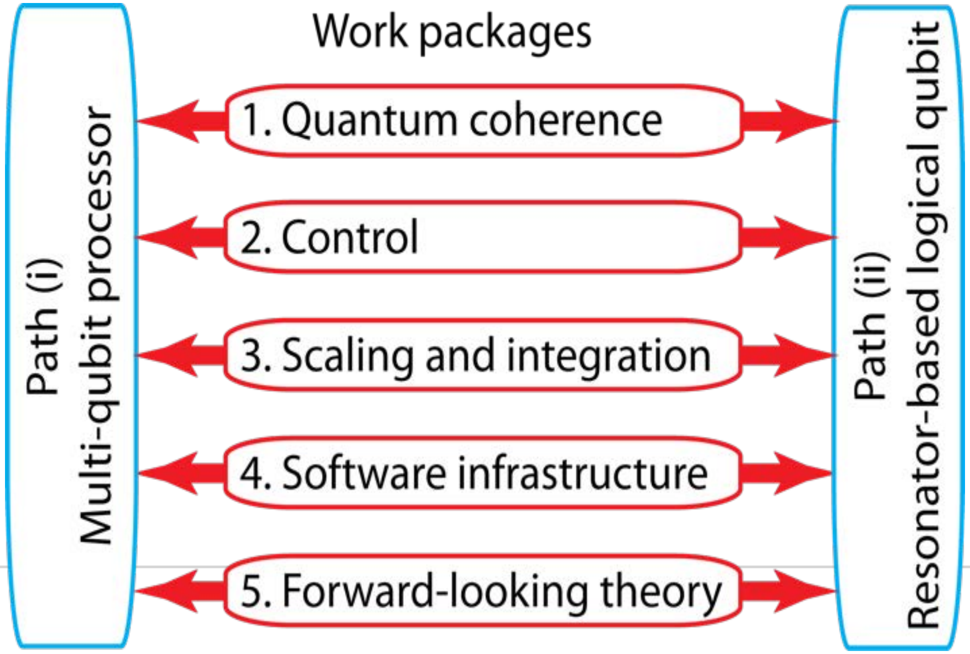
Goal: **To build a quantum computer with100 superconducting qubits after 10 years**

Location: **Chalmers**

Two tracks: **i) Multi qubit platform**
ii) Resonator based Cat-qubits



- Long lived qubits
- Fast electronics to control and read out qubits.
- Integrating many qubits and coupling them together
- Developing efficient software to run quantum algorithms.
- Find the right problems to solve.



Work packages

Path (i) Multi-qubit processor

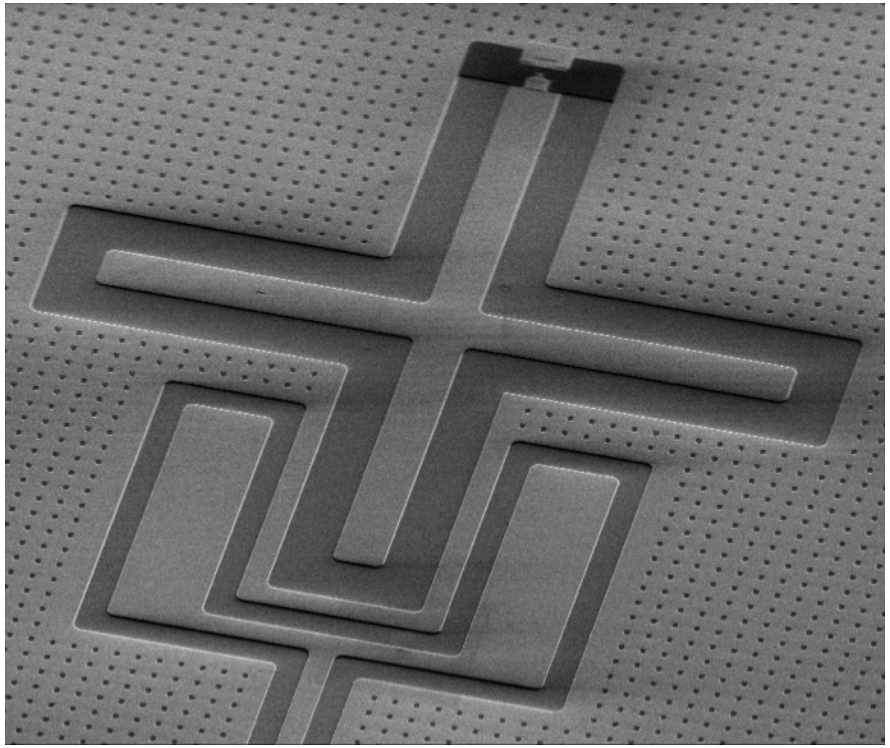
1. Quantum coherence
2. Control
3. Scaling and integration
4. Software infrastructure
5. Forward-looking theory

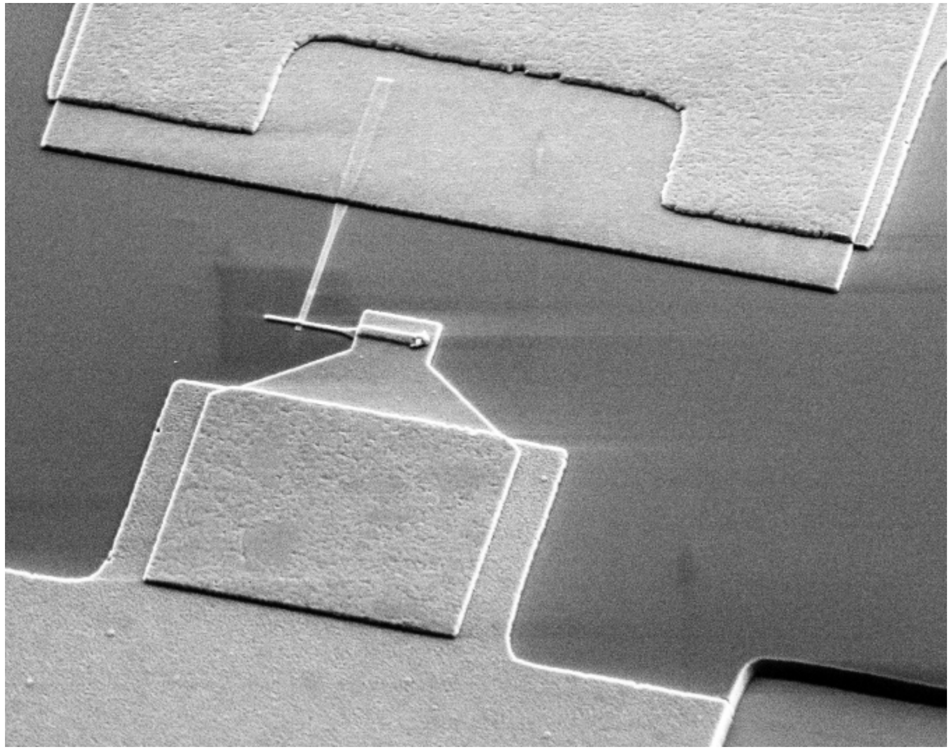
Path (ii) Resonator-based logical qubit

The qubits

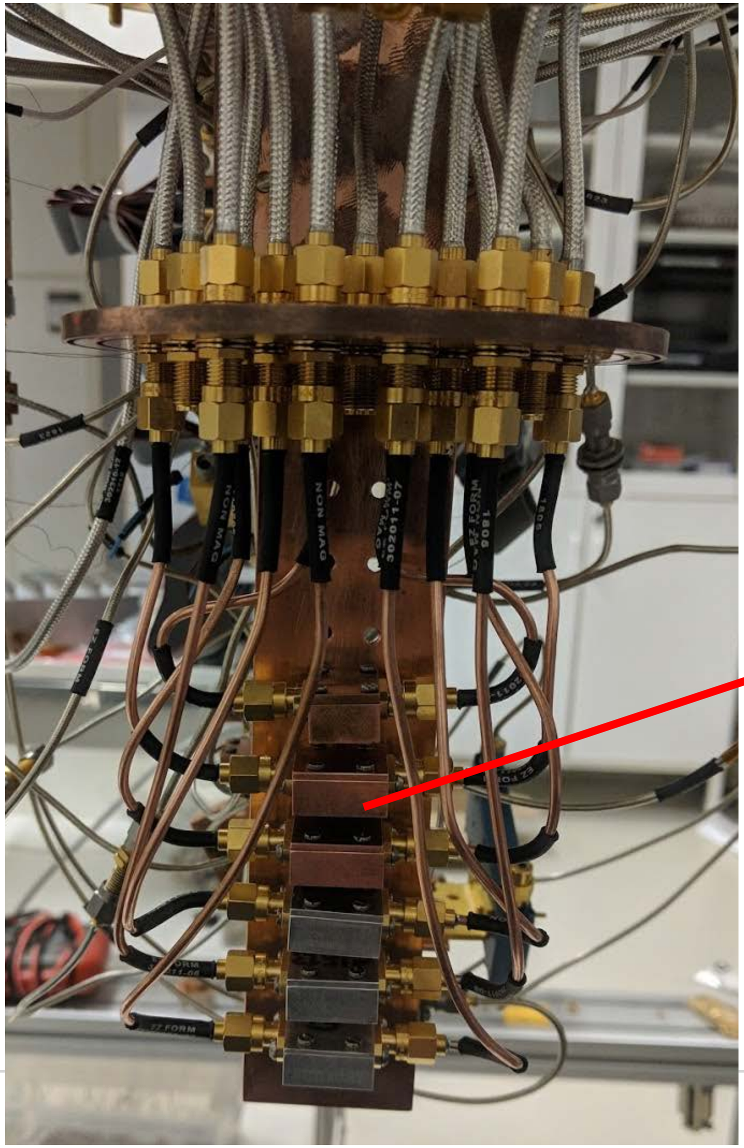
- A 4-armed superconducting qubit with a C-shaped coupler to a superconducting resonator.

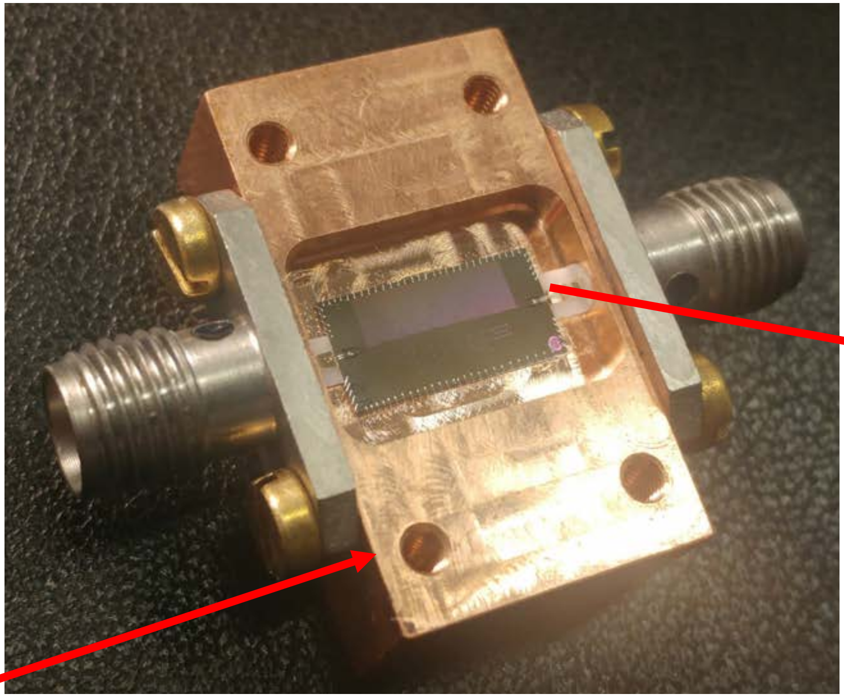
A Josephson junction which is located on the top arm of the qubit.

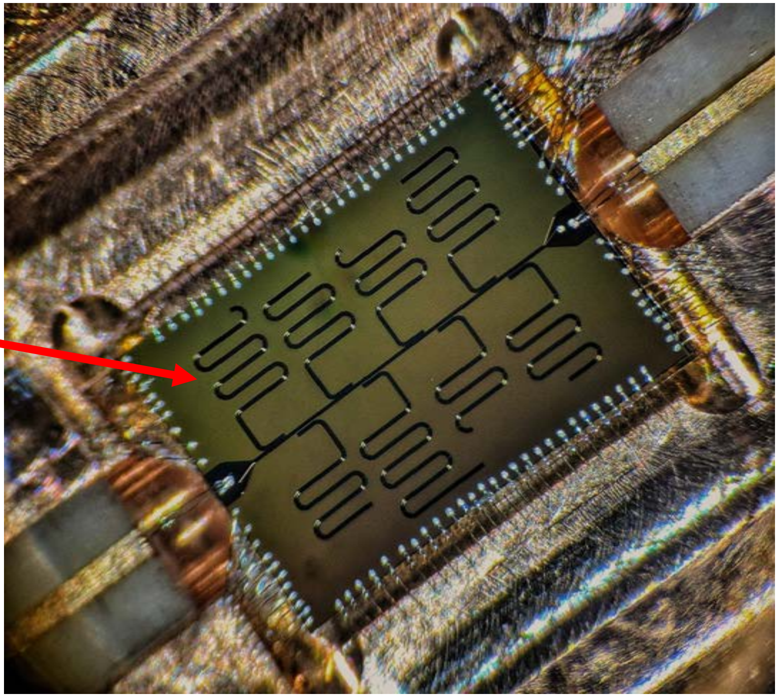




Superconducting circuits



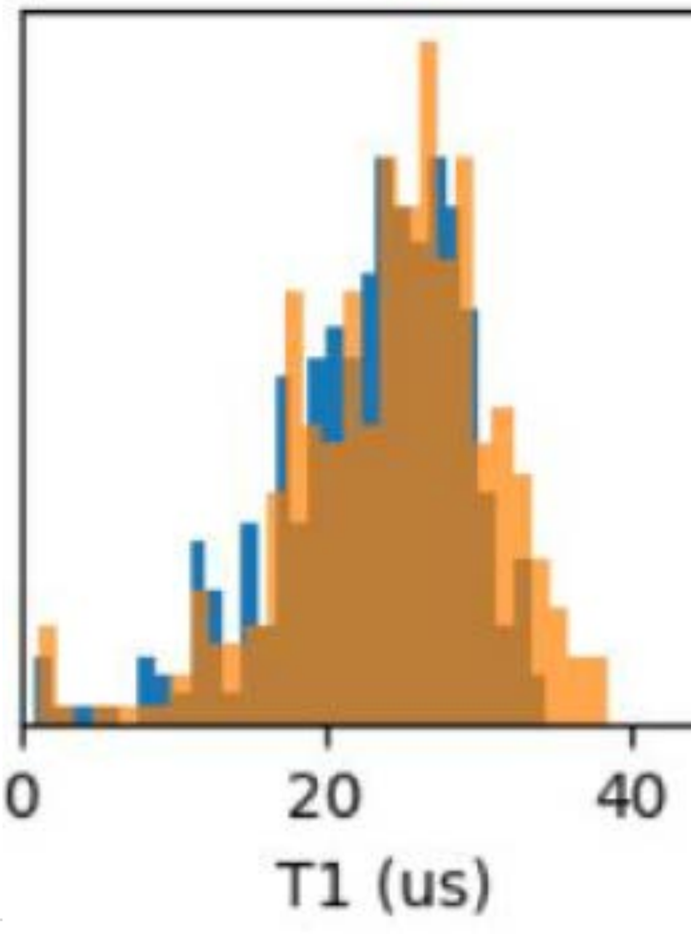




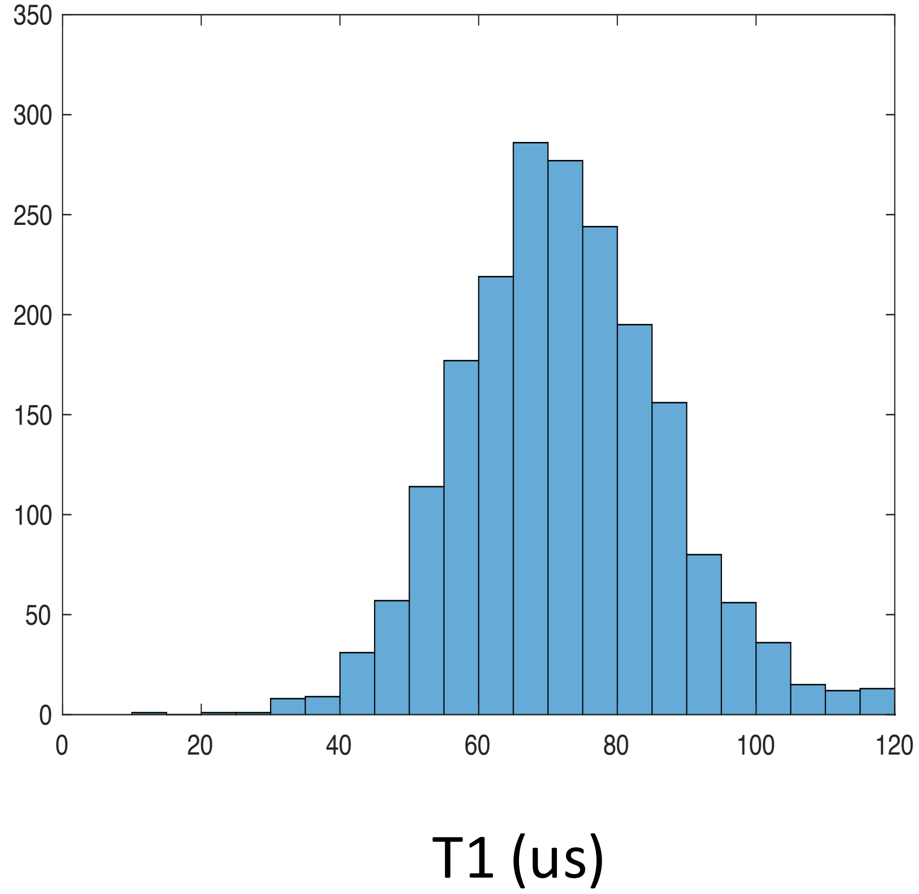
- Copper or Aluminium sample enclosure
- Al wire-bonding to non-mag SMA connector
- Al thin film (superconductor) patterned into co-planer microwave circuits

Progress on qubits

Google, recent PRL
T1_mean 25μs

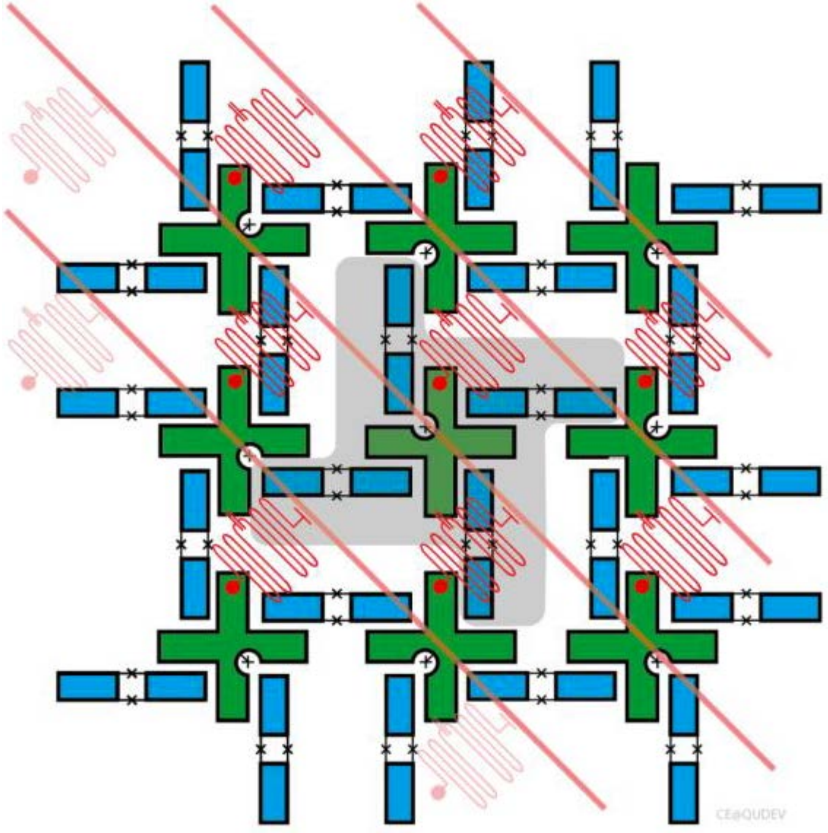


Chalmers T1s (unpublished)
T1_mean 72 μs



The Architecture, multi-qubit processor

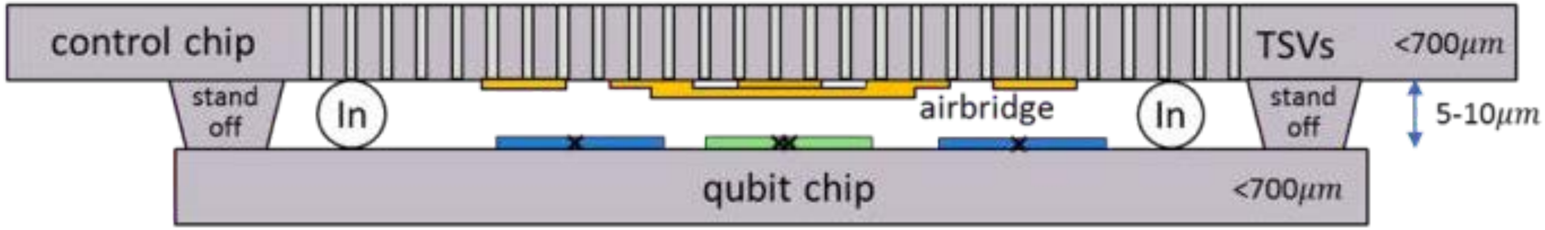
Scalable architecture, in collaboration with ETH and other partners within the QT-Flagship



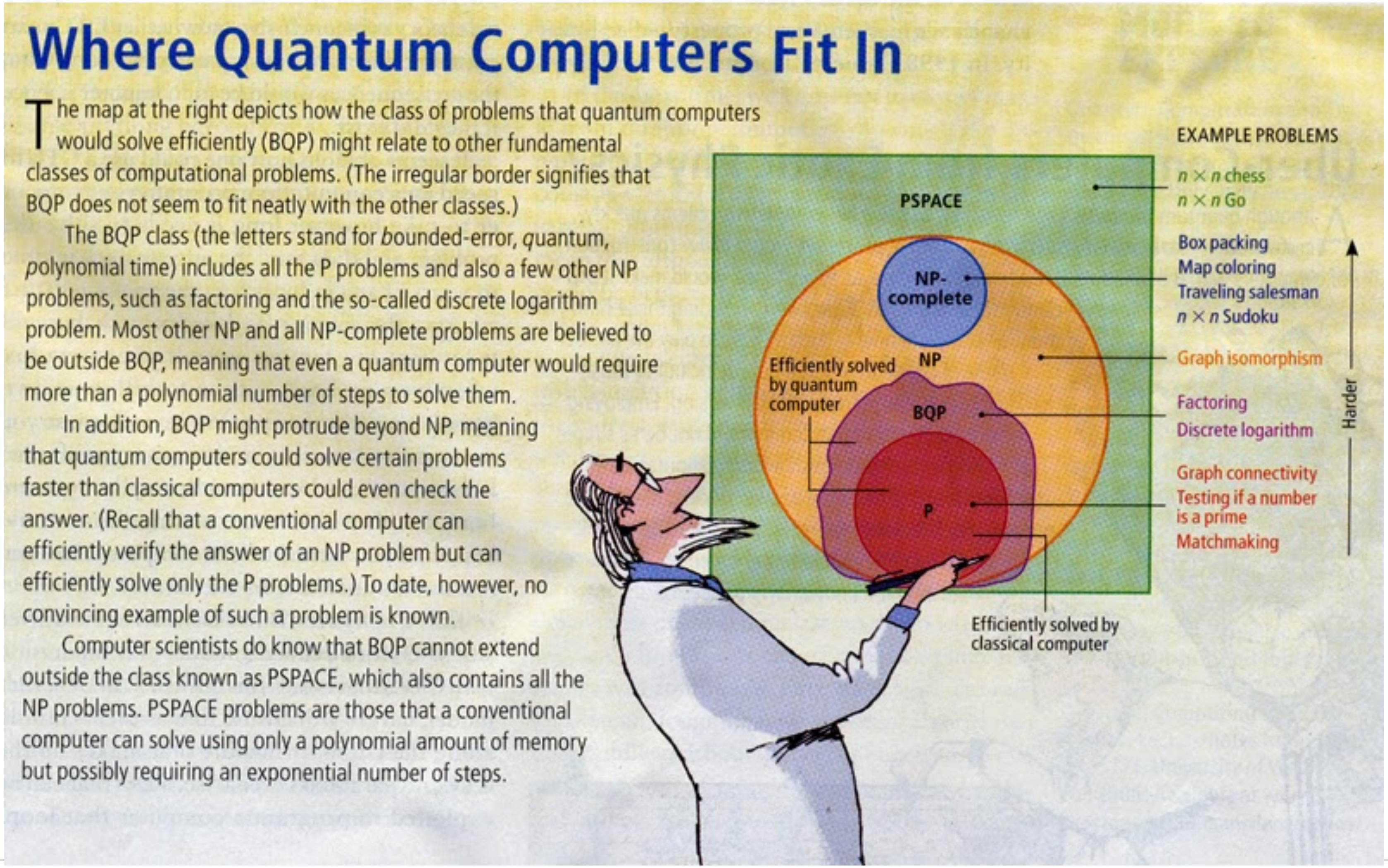
Fixed-frequency transmon qubits form a 2D array.

Neighboring qubits are coupled via tunable couplers, which can be RF modulated to parametrically drive qubit-qubit interactions.

Control lines and elements for readout are hosted on a separate control chip.



Classes of problems



Where Quantum Computers Fit In

The map at the right depicts how the class of problems that quantum computers would solve efficiently (BQP) might relate to other fundamental classes of computational problems. (The irregular border signifies that BQP does not seem to fit neatly with the other classes.)

The BQP class (the letters stand for *bounded-error, quantum, polynomial time*) includes all the P problems and also a few other NP problems, such as factoring and the so-called discrete logarithm problem. Most other NP and all NP-complete problems are believed to be outside BQP, meaning that even a quantum computer would require more than a polynomial number of steps to solve them.

In addition, BQP might protrude beyond NP, meaning that quantum computers could solve certain problems faster than classical computers could even check the answer. (Recall that a conventional computer can efficiently verify the answer of an NP problem but can efficiently solve only the P problems.) To date, however, no convincing example of such a problem is known.

Computer scientists do know that BQP cannot extend outside the class known as PSPACE, which also contains all the NP problems. PSPACE problems are those that a conventional computer can solve using only a polynomial amount of memory but possibly requiring an exponential number of steps.

Scott Aaronson, Scientific American (2008)

NIST Quantum Algorithm Zoo lists all known quantum algorithms

What can the quantum computer do

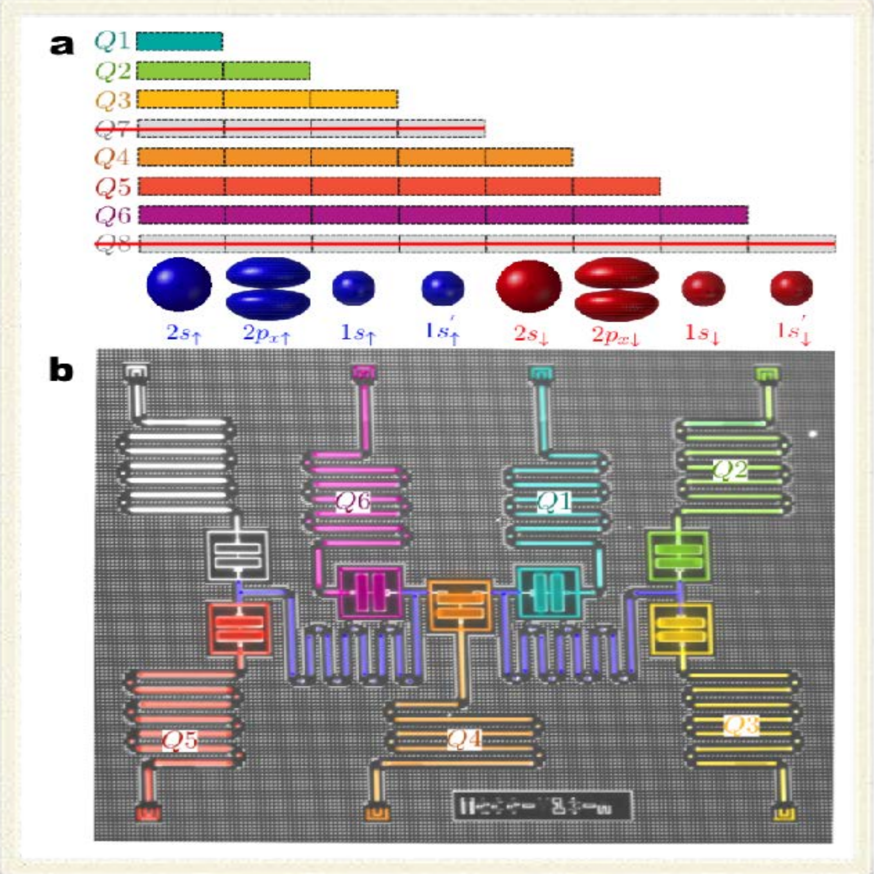
What program to run first?

- Limited coherence time implies limited running time (before error correction is implemented)
- Simulating 100 qubits is still too memory intensive for a classical supercomputer
- The answer should fit into the 100 bit output

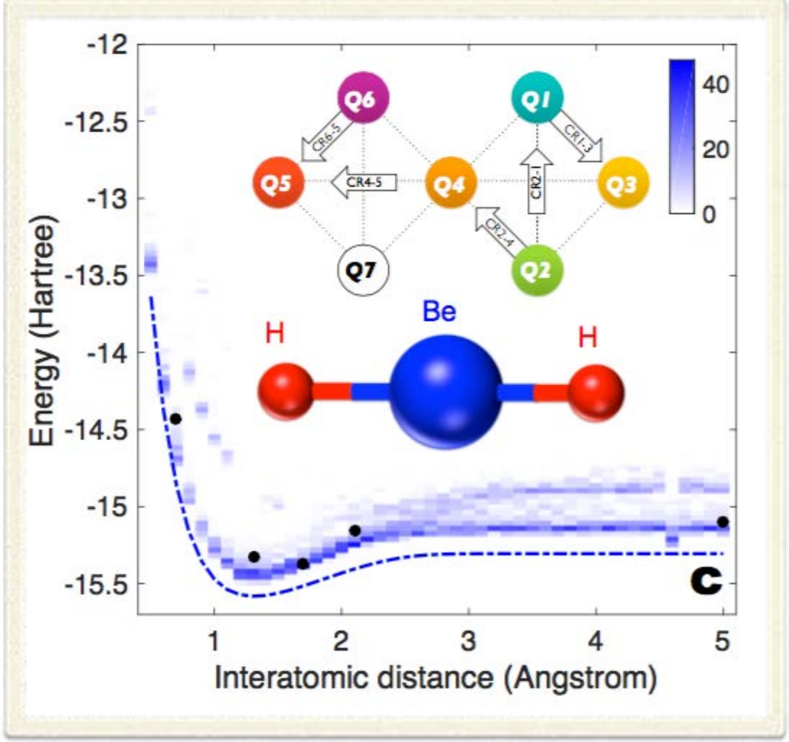
A few examples follow

Quantum Chemistry

find new catalysts and stable drug molecules



”Hardware-efficient Quantum Optimizer for Small Molecules and Quantum Magnets”, Abhinav Kandala, Antonio Mezzacapo, Kristan Temme, Maika Takita, Jerry M. Chow, and Jay M. Gambetta (IBM), Nature 549, 242 (2017)

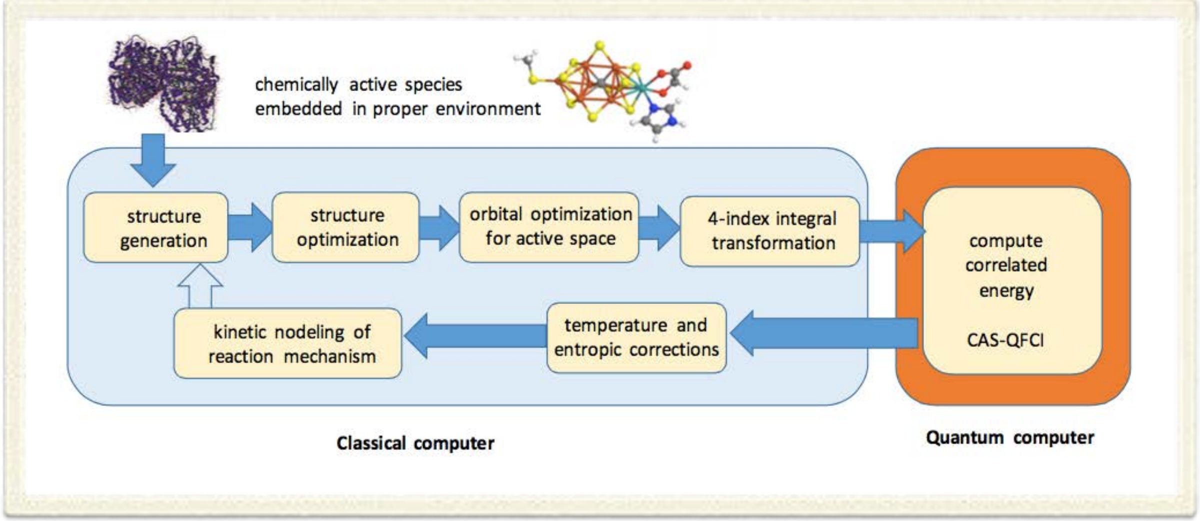


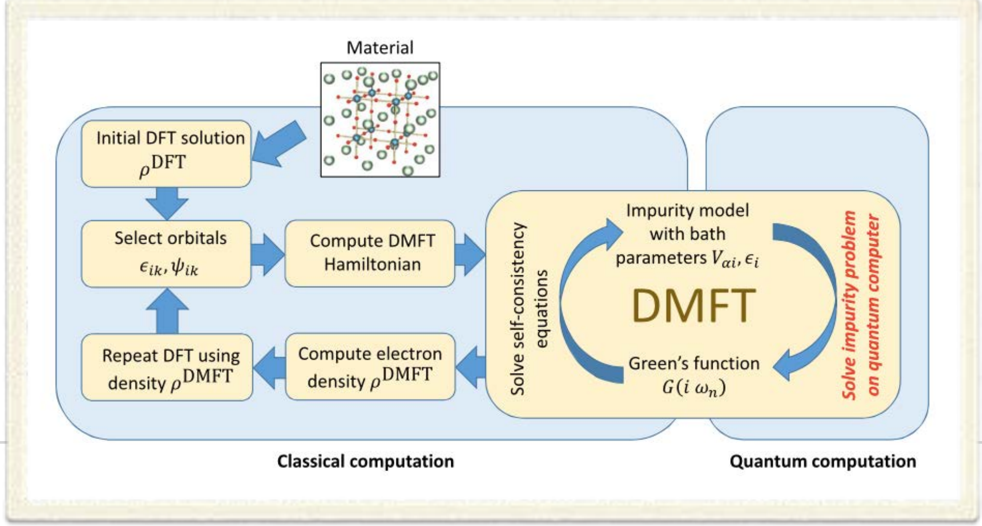
6 qubits + 2 buses + 6 read-out cavities

Eliminating bottlenecks

in quantum chemistry and material modeling

”Elucidating Reaction Mechanisms on Quantum Computers”,
M. Reiher, N. Wiebe, K. Svore, D. Wecker and M. Troyer.
arXiv:1605.03590(2016)

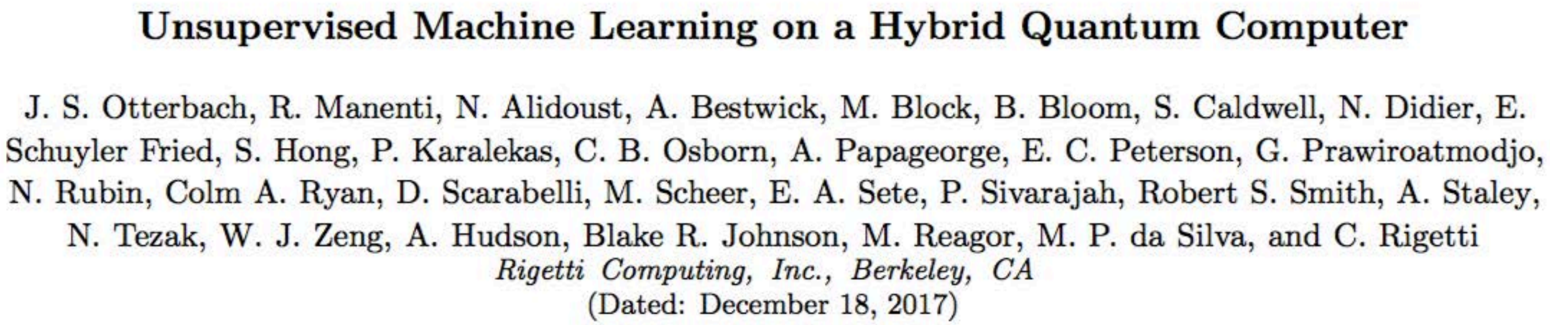




”Hybrid Quantum-Classical Approach to Correlated Materials ”,
Bela Bauer, Dave Wecker, Andrew J. Millis, Matthew B. Hastings and Matthias Troyer,
Physical Review X **6**, 031045 (2016)

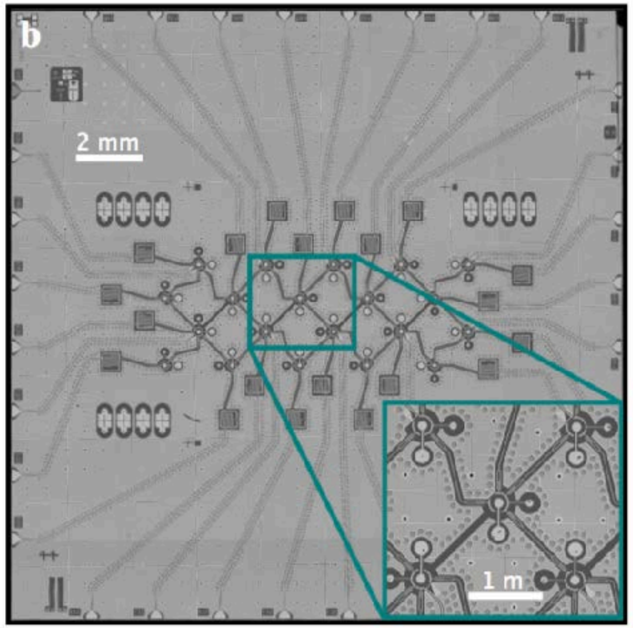
Quantum Computing for Finance

- The Black-Sholes equation for analysing financial derivatives is similar to the Schrödinger equation
- A quantum computer could find new patterns and explore more scenarios in financial models



Unsupervised Machine Learning on a Hybrid Quantum Computer

J. S. Otterbach, R. Manenti, N. Alidoust, A. Bestwick, M. Block, B. Bloom, S. Caldwell, N. Didier, E. Schuyler Fried, S. Hong, P. Karalekas, C. B. Osborn, A. Papageorge, E. C. Peterson, G. Prawiroatmodjo, N. Rubin, Colm A. Ryan, D. Scarabelli, M. Scheer, E. A. Sete, P. Sivarajah, Robert S. Smith, A. Staley, N. Tezak, W. J. Zeng, A. Hudson, Blake R. Johnson, M. Reagor, M. P. da Silva, and C. Rigetti
Rigetti Computing, Inc., Berkeley, CA
(Dated: December 18, 2017)



19 qubit processor

npj | Quantum Information www.nature.com/npjqi

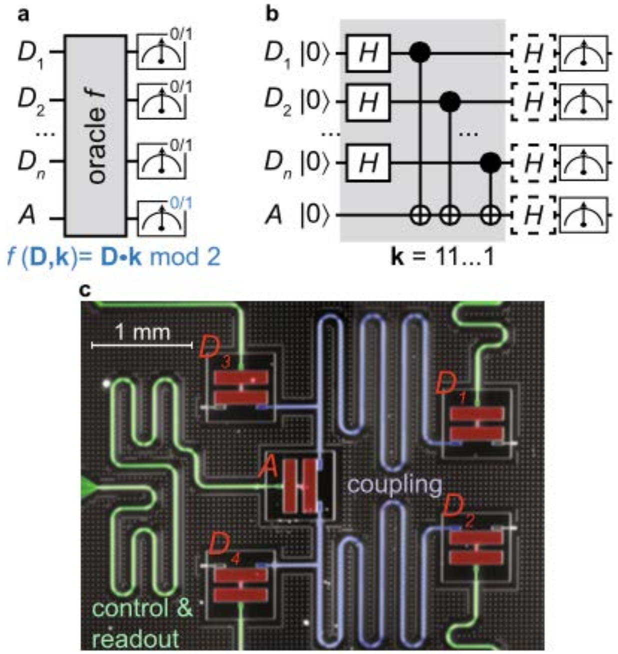
March 2017

ARTICLE **OPEN**

Demonstration of quantum advantage in machine learning

Diego Ristè[1], Marcus P. da Silva[1], Colm A. Ryan[1], Andrew W. Cross[2], Antonio D. Córcoles[2], John A. Smolin[2], Jay M. Gambetta[2], Jerry M. Chow[2] and Blake R. Johnson[1]

IBM Q



”Learning Parity with Noise”

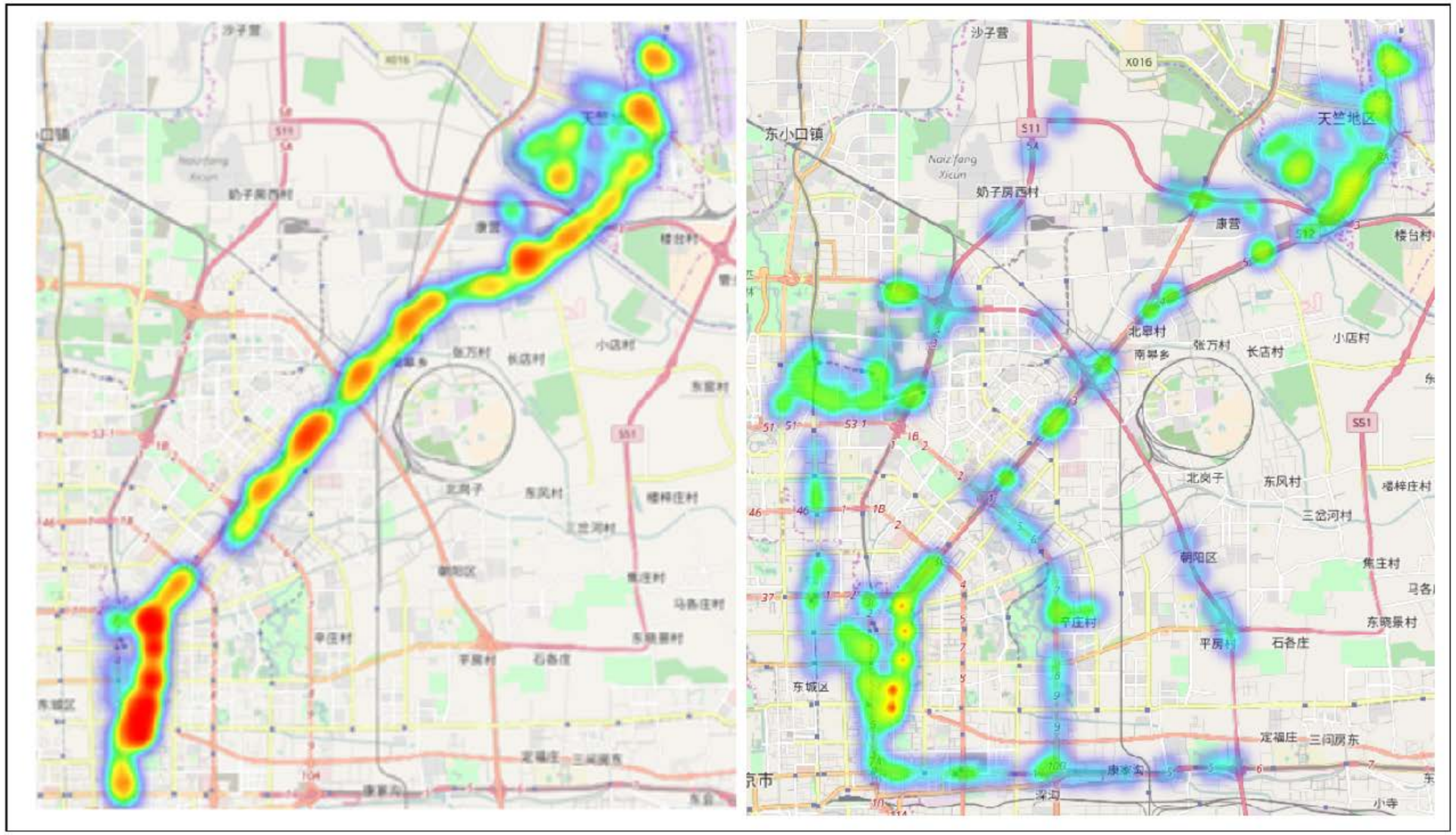
5 qubit processor

Logistics I

optimizing transport solutions, taxis in Shanghai

Without optimization

With optimization



Red markes slow trafic

Give each car 3 alternative routes and optimise

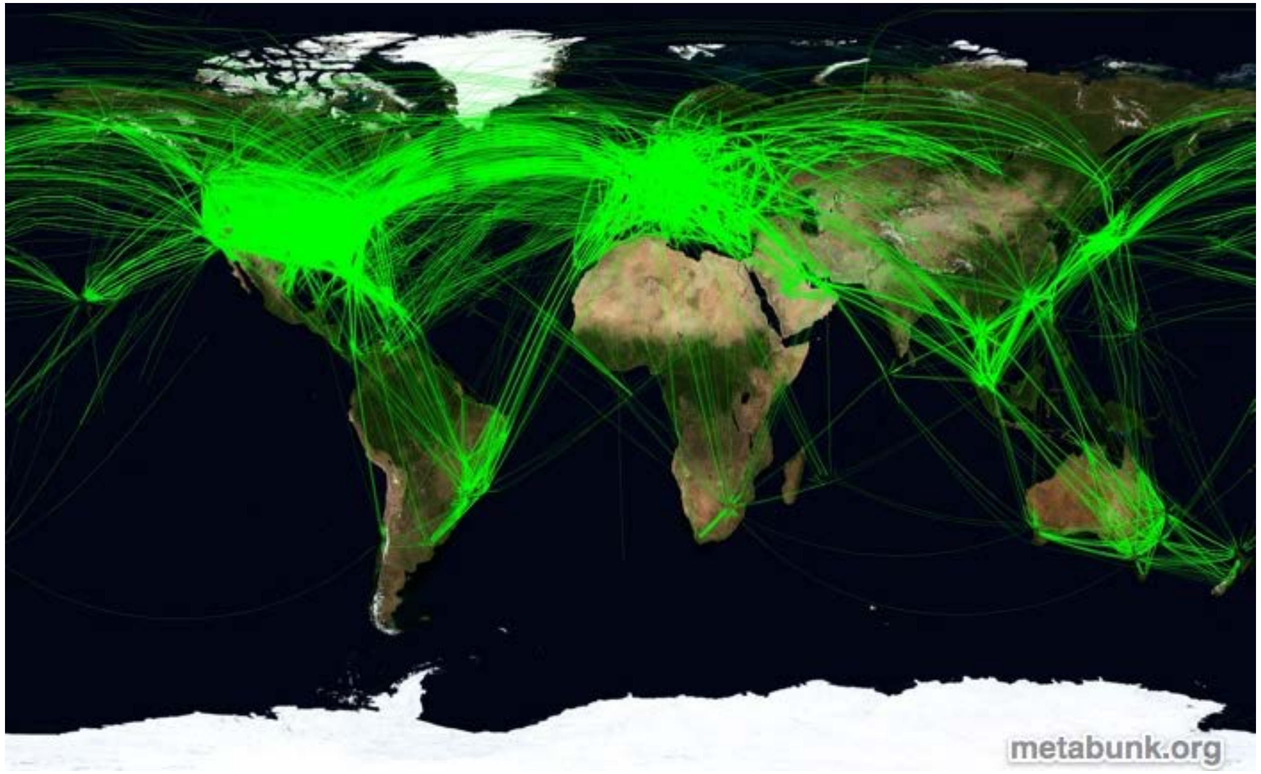
VW Data in Munich

Logistics II

Optimizing airline routes and crews

100 destinations and 100 airplanes	10^{157} possibilities
100 destinations and 100 airplanes and 100 crews	10^{315} possibilities

~10^{90} particles in the universe



This problem can be mapped to a the problem of finding the ground state of a Hamiltonian

Quantum computers,
how do they work and what can they do?

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