GOOGLE QUANTUM COMPUTING PROJECT

Department of Information and Communication Engineering
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GROUP 001 | ICE 17-1

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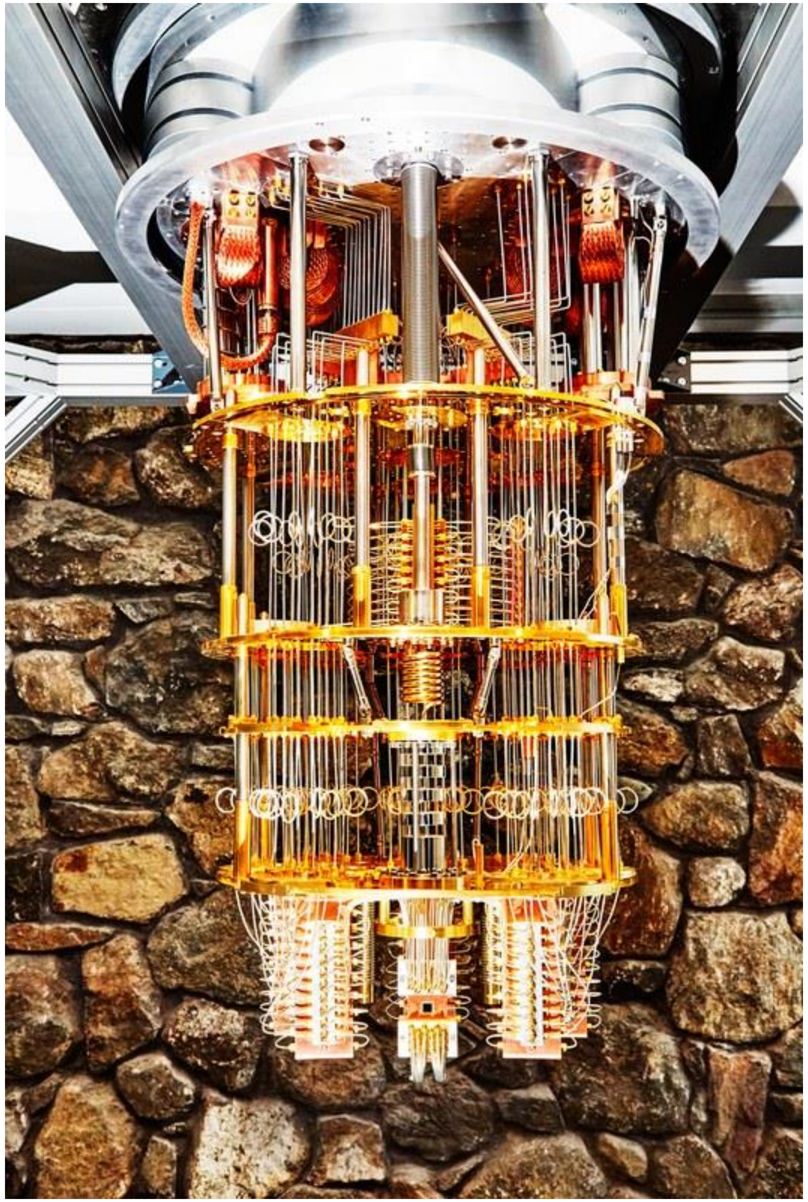
Google AI
Quantum

What is a quantum computer?

Speaker: Saydakhmatova Ziyoda U1710259

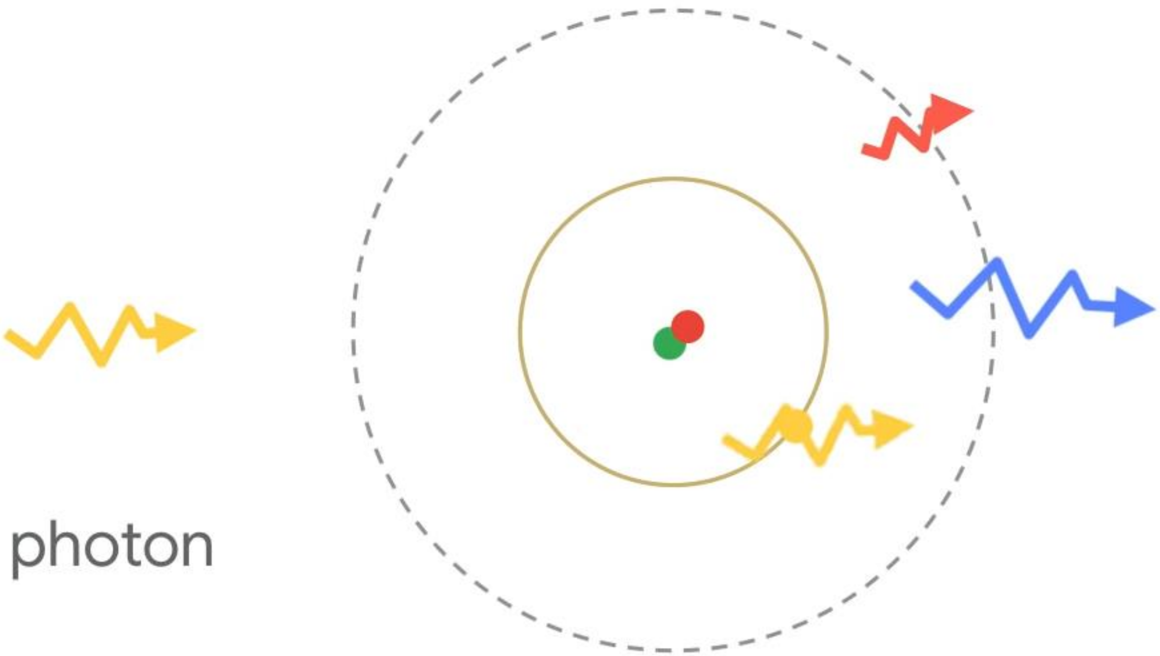
Introduction to Quantum Computing



Quantum computer (view from inside)

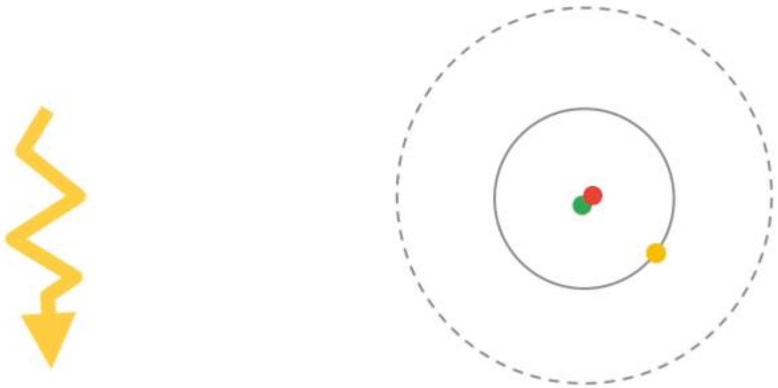
- In physics, a "**quantum**" (plural: quanta) is the smallest amount of energy (physical property) capable of being lost or gained by a system. The change of energy related to a quantum is too small and is only perceptible on atomic scales.
- Quantum computing is the use of quantum-mechanical phenomena such as **superposition** and entanglement to perform computation.
- A quantum computer is a machine designed to use the principles of **quantum mechanics** to do things which are fundamentally impossible for any computer which only uses classical physics.
- Quantum mechanics deals with very small systems, like **atoms** or **protons** ("particles of light")

Quantum mechanics



Quantum

"Energy comes in discrete packets"

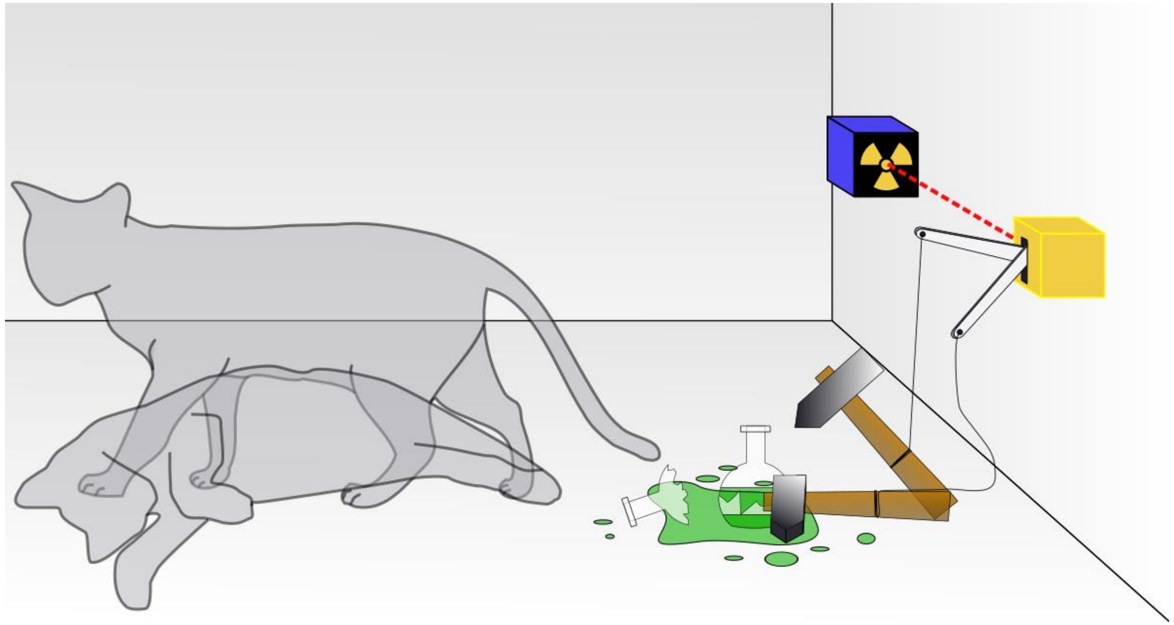


Quantum objects

bits	qubits
b_0	$c_0\|0\rangle + c_1\|1\rangle$
b_0b_1	$c_0\|00\rangle + c_1\|01\rangle + c_2\|10\rangle + c_3\|11\rangle$
$b_0b_1b_2$	$c_0\|000\rangle + c_1\|001\rangle + c_2\|010\rangle + c_3\|011$ $c_4\|100\rangle + c_5\|101\rangle + c_6\|110\rangle + c_7\|111$
$b_0b_1b_2b_3$	$c_0\ \|0000\rangle + c_1\ \|0001\rangle + c_2\ \|0010\rangle +$ $c_3\ \|0011\rangle + c_4\ \|0100\rangle + c_5\ \|0101\rangle +$ $c_6\ \|0110\rangle + c_7\ \|0111\rangle + c_8\ \|1000\rangle +$ $c_9\ \|1001\rangle + c_{10}\|1010\rangle + c_{11}\|1011\rangle +$ $c_{12}\|1100\rangle + c_{13}\|1101\rangle + c_{14}\|1110\rangle +$ $c_{15}\|1111\rangle$

Key ingredient of quantum mechanics – superposition

Schrödinger's cat is a thought experiment, sometimes described as a paradox, devised by Austrian physicist Erwin Schrödinger in 1935. It illustrates what he saw as the problem of the Copenhagen interpretation of quantum mechanics applied to everyday objects. The scenario presents a hypothetical cat that may be simultaneously both alive and dead, a state known as a quantum superposition, as a result of being linked to a random subatomic event that may or may not occur.

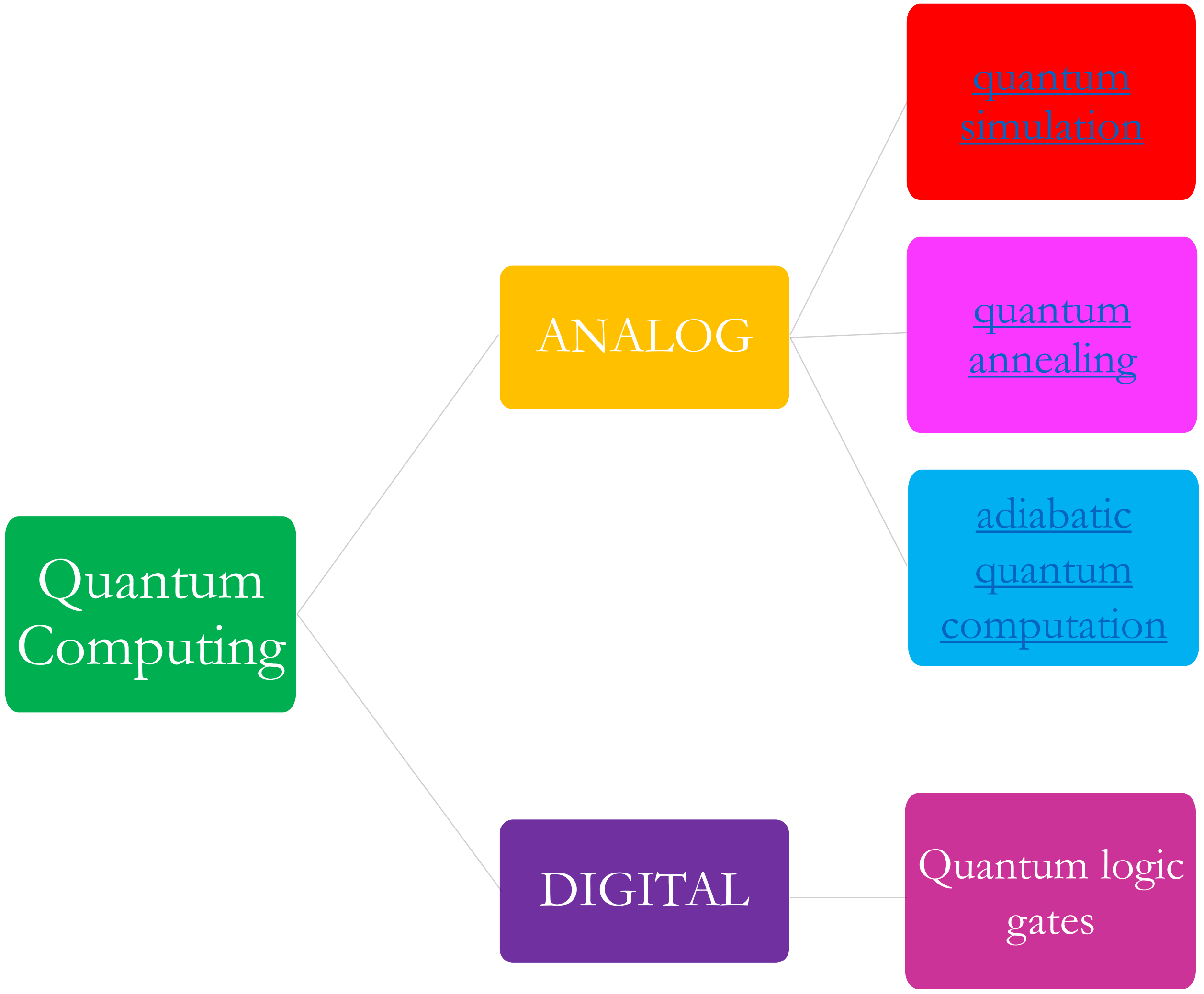


If a system can be in state A or state B, it can also be in a "mixture" of the two states. If we measure it, we see either A or B, probabilistically

Types of Quantum Computing

There are **two** main approaches to physically implementing a quantum computer currently, analog and digital.

- **Analog** approaches are further divided into quantum simulation, quantum annealing, and adiabatic quantum computation.
- **Digital** quantum computers use quantum logic gates to do computation. Both approaches use quantum bits or qubits.



Data representation

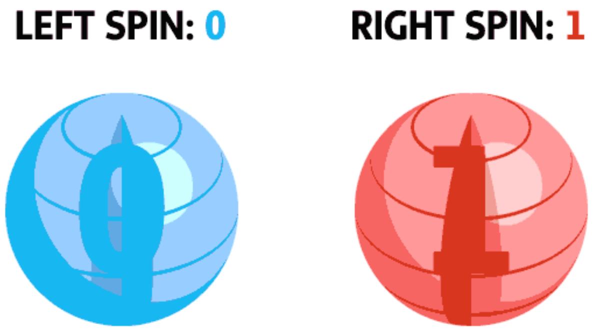
A quantum bit or qubit is a unit of quantum information, in same way as bit for ordinary computers.

Many different physical objects can be used as qubits such as atom, protons, or electrons.

Exists as ‘0’, a ‘1’ or simultaneously as a superposition of both ‘0’ and ‘1’.

Superposition occur all the time in the quantum level

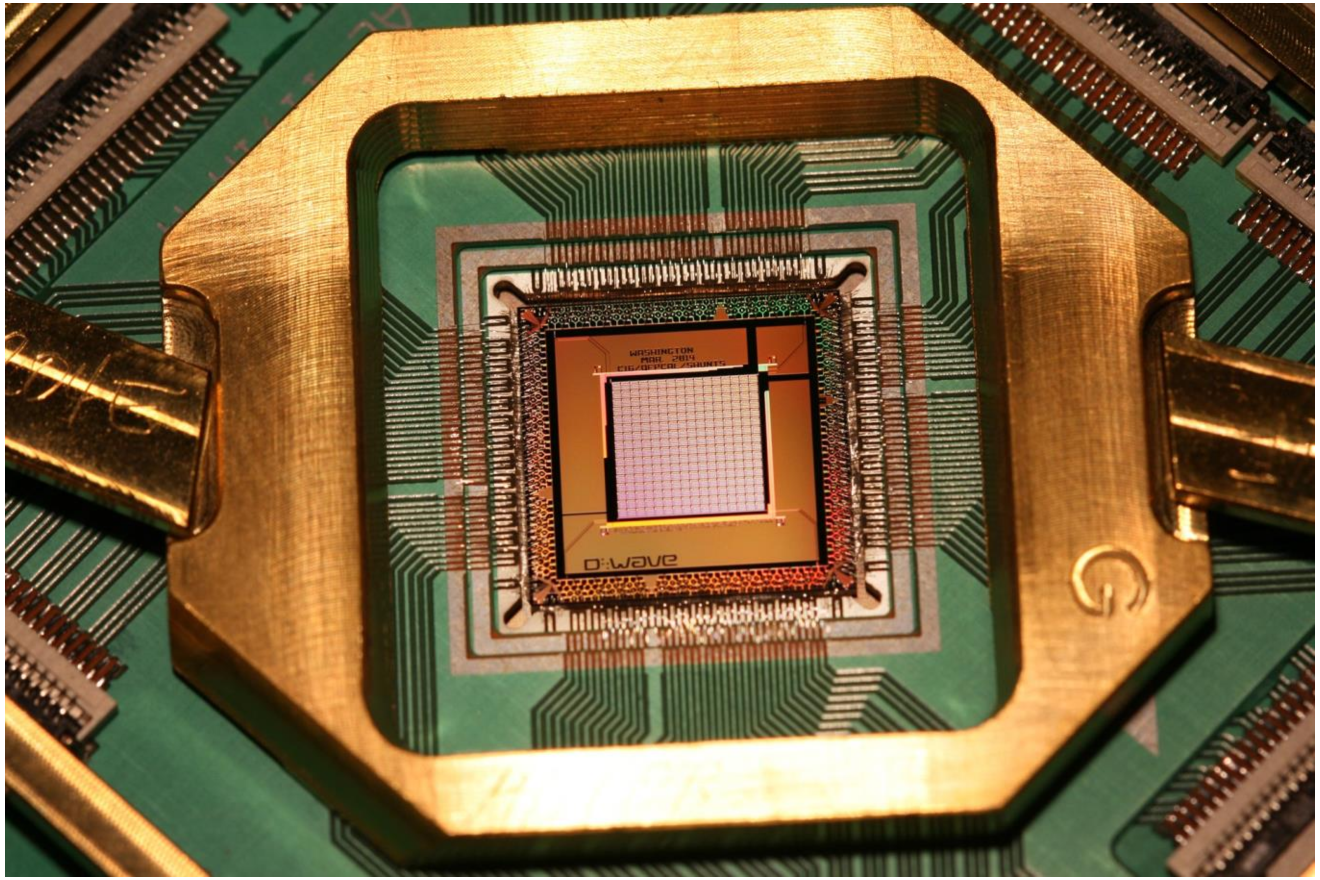
For example, one property of a photon is polarisation: a photon can be either vertically or horizontally polarised (↑or→), so this gives us a qubit.



Quantum computer

When you see pictures of "a quantum computer," usually you notice the cryostat—which is bigger than a person. But that's just the shell, providing the proper environment for the processor to function.

The quantum processor itself is a silicon chip installed in the cryostat, and is closer to the size of a coin. The qubits are small, roughly 0.1 mm across, but not that small—you can see them with the naked eye (though it's easier with a magnifying glass or microscope).



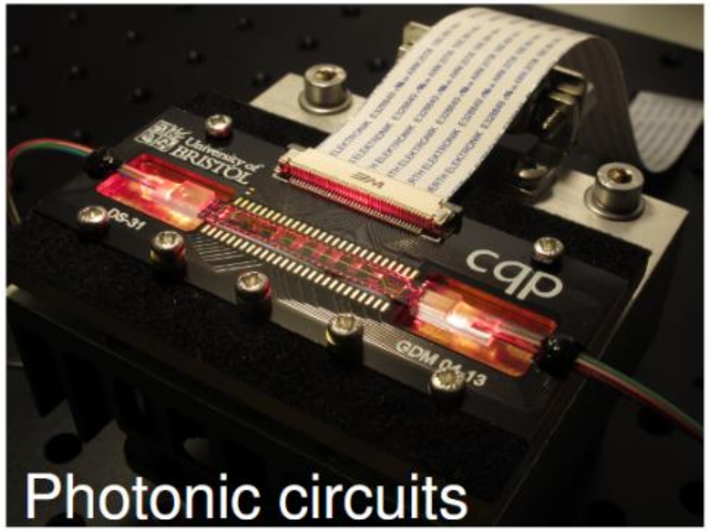
Classic Computers	Quantum Computers
Conventional computing is based on the classical phenomenon of electrical circuits being in a single state at a given time, either on or off.	Quantum computing is based on the phenomenon of Quantum Mechanics, such as superposition and entanglement, the phenomenon where it is possible to be in
Information storage and manipulation is based on "bit", which is based on voltage or charge; low is 0 and high is 1.	Information storage and manipulation is based on Quantum Bit or "qubit", which is based on the spin of electron or polarization of a single photon.
The circuit behavior is governed by classical physics.	The circuit behavior is governed by quantum physics or quantum mechanics.
Conventional computing use binary codes i.e. bits 0 or 1 to represent information.	Quantum computing use Qubits i.e. 0, 1 and superposition state of both 0 and 1 to represent information.
CMOS transistors are the basic building blocks of conventional computers.	Superconducting Quantum Interference Device or SQUID or Quantum Transistors are the basic building blocks of quantum computers.
In conventional computers, data processing is done in Central Processing Unit or CPU, which consists of Arithmetic and Logic Unit (ALU), processor registers and a control unit.	In quantum computers, data processing is done in Quantum Processing Unit or QPU, which consists of a number of interconnected qubits

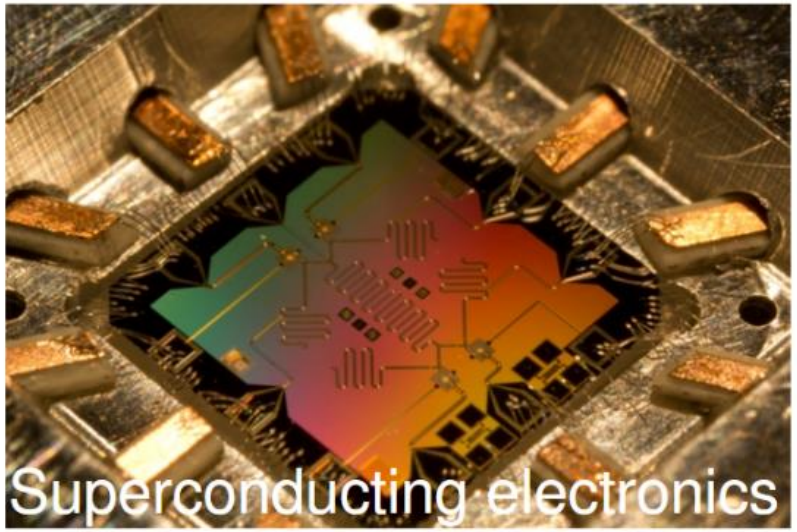
Quantum computing technologies

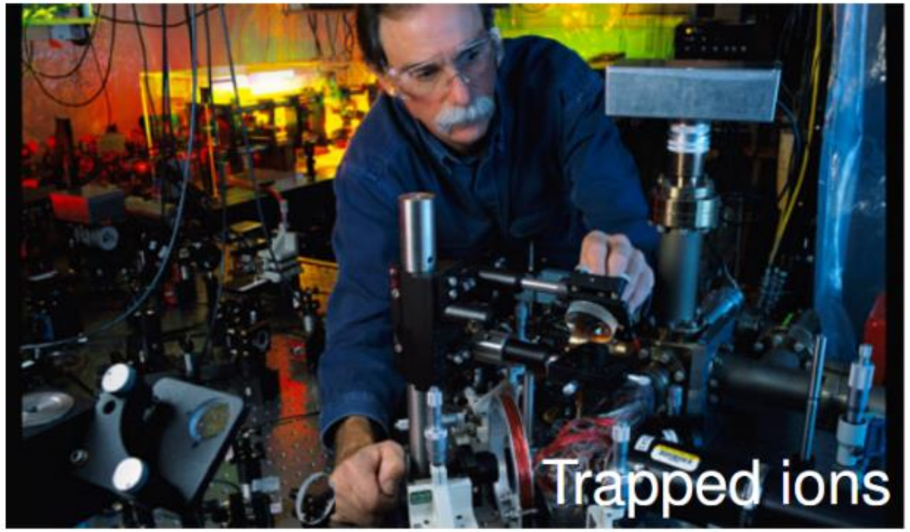
It isn't clear yet which technology will be used to build a large-scale quantum computer.

Some examples:

1. Photonic circuits
2. Superconducting electronics
3. Trapped icons

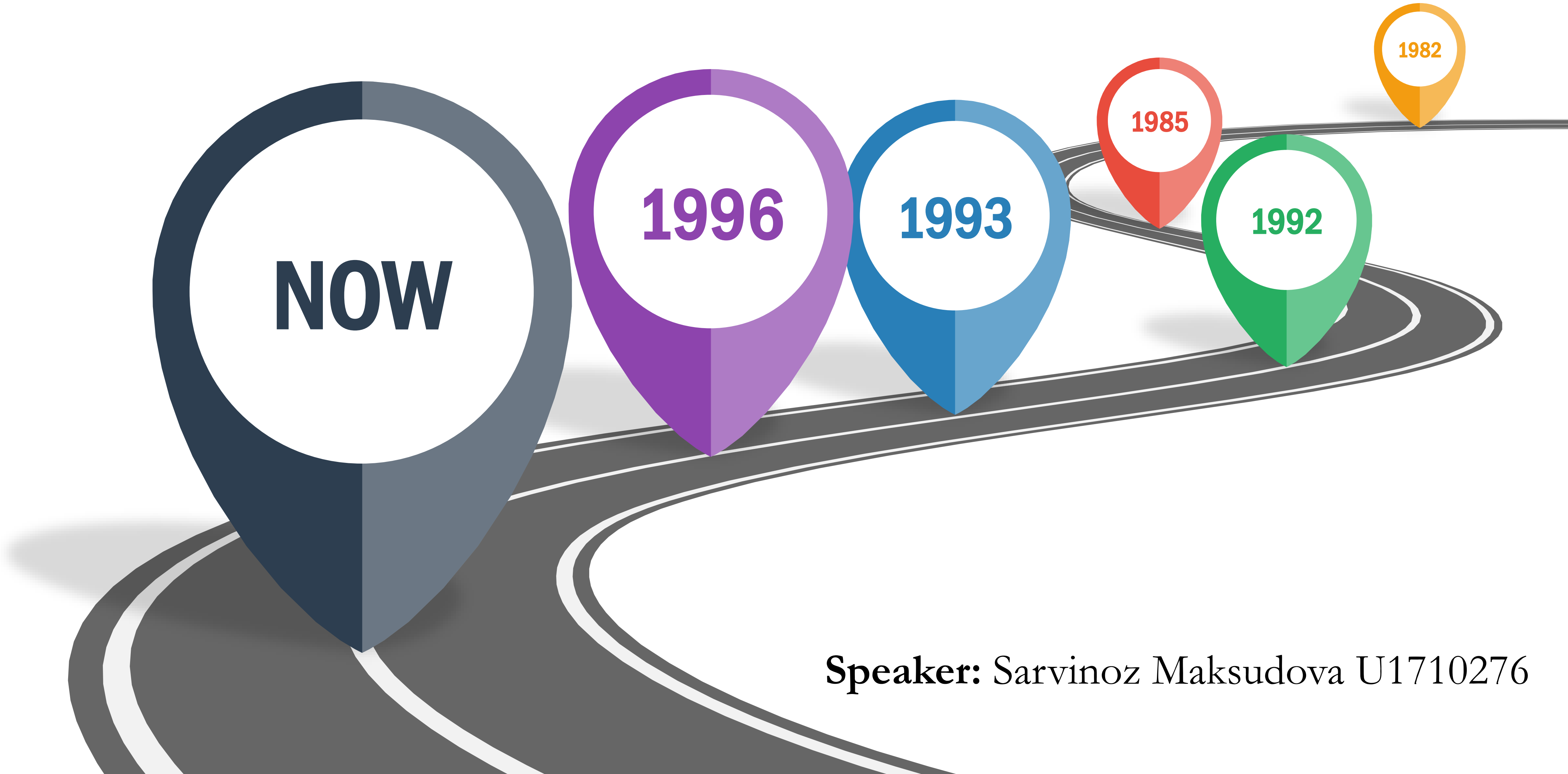






History of Quantum Computing

brief overview of the main events in the timeline of quantum computing and quantum mechanics



Speaker: Sarvinoz Maksudova U1710276

There is no efficient general-purpose method known to simulate quantum physics on a standard computer.

- 1982: Nobel Laureate Richard Feynman asked whether quantum physics could be simulated efficiently using a quantum computer.

"If you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Pic: Wikipedia/Richard Feynman

But nobody knew what such a quantum computer would look like. . .

- 1985: David Deutsch proposes the mathematical concept of the quantum Turing machine to model quantum computation.

"Computing devices resembling the universal quantum computer can, in principle, be built and would have many remarkable properties not reproducible by any Turing machine."

Pic: www.physics.ox.ac.uk/al/people/Deutsch.htm

This put the concept of quantum computing on a sound theoretical footing for the first time.

But could a quantum computer actually outperform a classical computer?

- 1992: David Deutsch and Richard Jozsa give the first such example.

"The quantum computation solves the problem with certainty in exponentially less time than any classical deterministic computation."

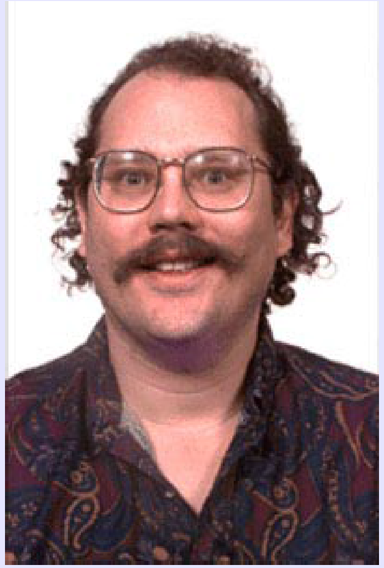
Pic: www.damtp.cam.ac.uk/people/r.jozsa

- 1993: Ethan Bernstein and Umesh Vazirani show that quantum computers can be significantly faster than classical computers, even if the classical computer is allowed a small probability of error.
- 1994: Dan Simon shows that quantum computers can be exponentially faster.

Shor's algorithm

But could a quantum computer solve a problem which people actually care about?

- 1994: Peter Shor shows that quantum computers can factorise large integers efficiently.



Pic: physik.uni-graz.at

Given an integer $N = p \times q$ for prime numbers p and q, Shor's algorithm outputs p and q.

No efficient classical algorithm for this task is known.

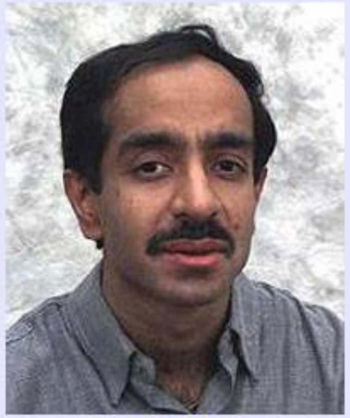
Grover's algorithm

One of the most basic problems in computer science: unstructured search.

- Imagine we have n boxes, each containing a 0 or a 1. We can look inside a box at a cost of one query.

0	0	1	0	0	0	1	0

- We want to find a box containing a 1. On a classical computer, this task could require n queries in the worst case.
- 1996: Lov Grover gives a quantum algorithm which solves this problem using about $\sqrt{n}$ queries.



Pic: Bell Labs

The square-root speedup of Grover's algorithm finds many applications to search and optimisation problems.

Quantum simulation

The third important algorithmic development in the late 90's was the resolution of Feynman's conjecture.

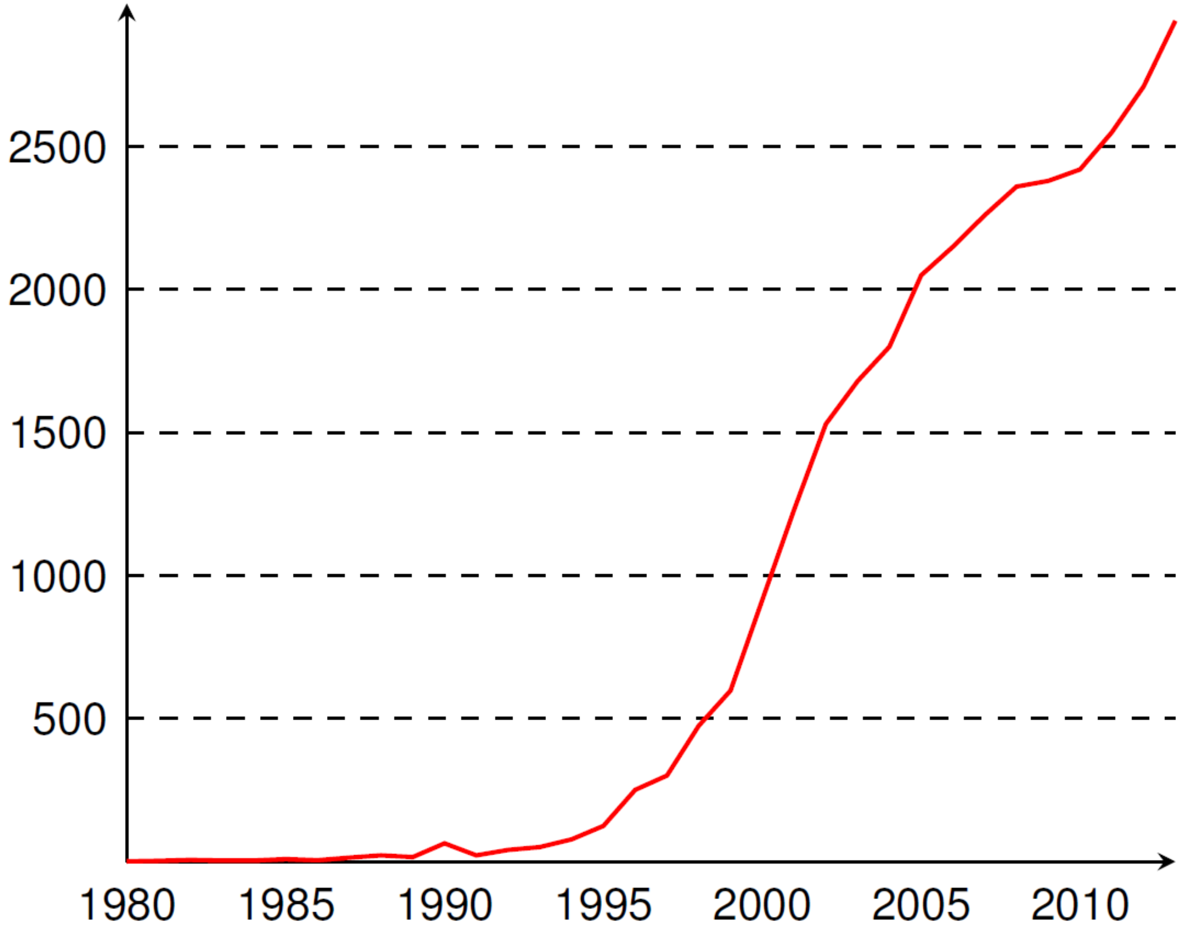
- 1996: Seth Lloyd proposes a quantum algorithm which can simulate quantum-mechanical systems.

Pic: MIT

"A quantum computer with a few tens of quantum bits could perform in a few tens of steps simulations that would require Avogadro's number [6×10^{23}] of memory sites and operations on a classical computer."

The rise of quantum computing

Following the publication of these algorithms, there was an explosion of interest in quantum computing:



Number of published papers using phase "quantum computer" per year (Google scholar)

Timeline from “suggestion” until Google’s quantum labs

1980	Physicist Paul Benioff suggests quantum mechanics could be used for computation.
1981	Nobel-winning physicist Richard Feynman, at Caltech, coins the term quantum computer.
1985	Physicist David Deutsch, at Oxford, maps out how a quantum computer would operate, a blueprint that underpins the nascent industry of today
1994	Mathematician Peter Shor, at Bell Labs, writes an algorithm that could tap a quantum computer’s power to break widely used forms of encryption.
2007	D-Wave, a Canadian start-up, announces a quantum computing chip it says can solve Sudoku puzzles, triggering years of debate over whether the company’s technology really works.
2013	Google teams up with NASA to fund a lab to try out D-Wave’s hardware
2014	Google hires the professor behind some of the best quantum computer hardware yet to lead its new quantum hardware lab.
2016	IBM puts some of its prototype quantum processors on the internet for anyone to experiment with, saying programmers need to get ready to write quantum code.
2017	Start-up Rigetti opens its own quantum computer fabrication facility

Speaker: Sevara Amirullaeva U1710142

Google

QUANTUM COMPUTING

Research areas

Superconducting qubit processors

Superconducting qubits with chip-based scalable architecture targeting two-qubit gate error < 0.5%. Bristlecone is our newest 72-qubit quantum processor.

Qubit metrology

Reducing two-qubit loss below 0.2% is critical for error correction. We are working on a quantum supremacy experiment, to approximately sample a quantum circuit beyond the capabilities of state-of-the-art classical computers and algorithms.

Quantum simulation

Simulation of physical systems is among the most anticipated applications of quantum computing. We especially focus on quantum algorithms for modelling systems of interacting electrons with applications in chemistry and materials science.

Quantum assisted optimization

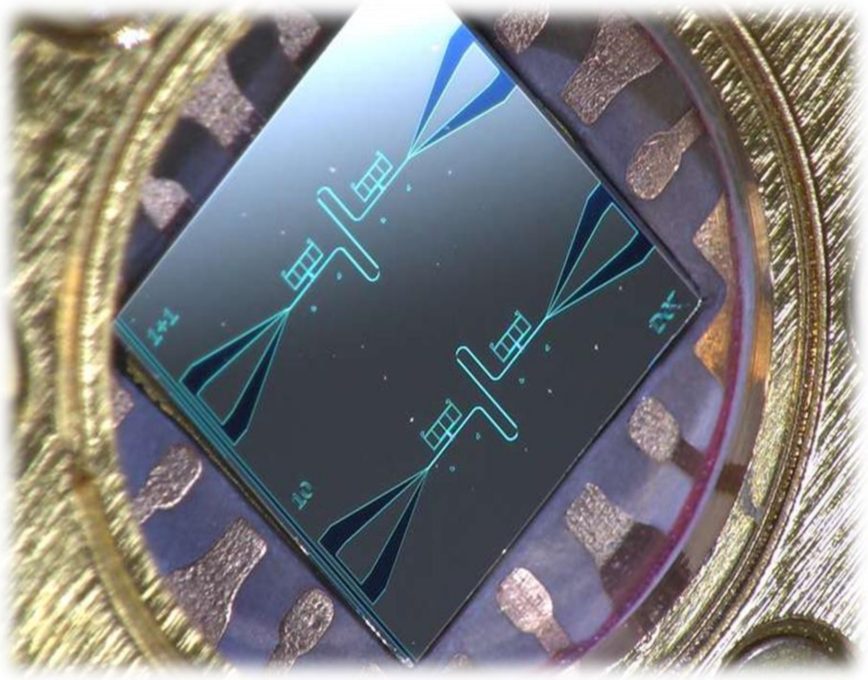
We are developing hybrid quantum-classical solvers for approximate optimization. Thermal jumps in classical algorithms to overcome energy barriers could be enhanced by invoking quantum updates. We are in particular interested in coherent population transfer.

Quantum neural networks

We are developing a framework to implement a quantum neural network on near-term processors. We are interested in understanding what advantages may arise from generate massive superposition states during operation of the network.

What are superconducting qubit processors

- One area of research the Google Quantum Labs is building quantum processors from superconducting electrical circuits, which are tempting tools for implementing quantum bits.
- Quantum computers need to keep their processors extremely cold and protect them from external shocks. Even accidental sounds can cause the computer to make mistakes.
- Superconductivity is the ability of certain metals to allow electricity to pass through them without any resistance at very low temperatures.



Google's Superconducting qubit processors

- Even if superconducting circuits have shown extensibility to modest processor sizes, the next challenge is stabilizing their performance, which can fluctuate unpredictably.
- Finally, to operate better, quantum processors need to have an error rate of less than 0.5 percent for every two qubits. Google's best has been 0.6 percent using its much smaller 9-qubit hardware. But recently Bristlecone - newest 72-qubit quantum processor which has an error rate of less than 0.5 percent was launched.

Manufacturer	Name/Code name/Designation	Architecture	Layout	Socket	Fidelity	Qubits	Release date
Google	N/A	Superconducting	N/A	N/A	99.5% [1]	20 qb	2017
Google	N/A	Superconducting	7×7 lattice	N/A	99.7% [1]	49 qb [2]	Q4 2017 (planned)
Google	Bristlecone	Superconducting	6×12 lattice	N/A	99% (readout) 99.9% (1 qubit) 99.4% (2 qubits)	72 qb [3][4]	5 March 2018

Qubit metrology

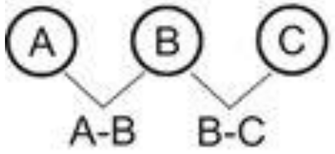
The biggest obstacle in building a fault-tolerant quantum computer is the need for high-fidelity qubit operations in a scalable architecture. Since only quantum error correction can overcome fundamental fragility of quantum information the challenge is to decrease the percentage of error.

Now **Google** is working on a quantum supremacy experiment, to approximately sample a quantum circuit beyond the capabilities of state-of-the-art classical computers and algorithms.

Google has already used these approaches in building newest quantum computers.

Qubit metrology: error correction

- In a fault-tolerant quantum computer the qubits and their logic interactions must have errors below a threshold: scaling up with more and more qubits then brings the net error probability down to appropriate levels.
- The key to quantum error correction is measuring qubit parities, which detects bit flips and phase flips in pairs of qubits. When parity changes, one of the two qubits had an error, but which one is not known. To identify, encoding must use larger numbers of qubits.



input bits			parity	
A	B	C	A-B	B-C
0	0	0	0	0
1	0	0	1	0
0	1	0	1	1
0	0	1	0	1
1	1	0	0	1
1	0	1	1	1
0	1	1	1	0
1	1	1	0	0

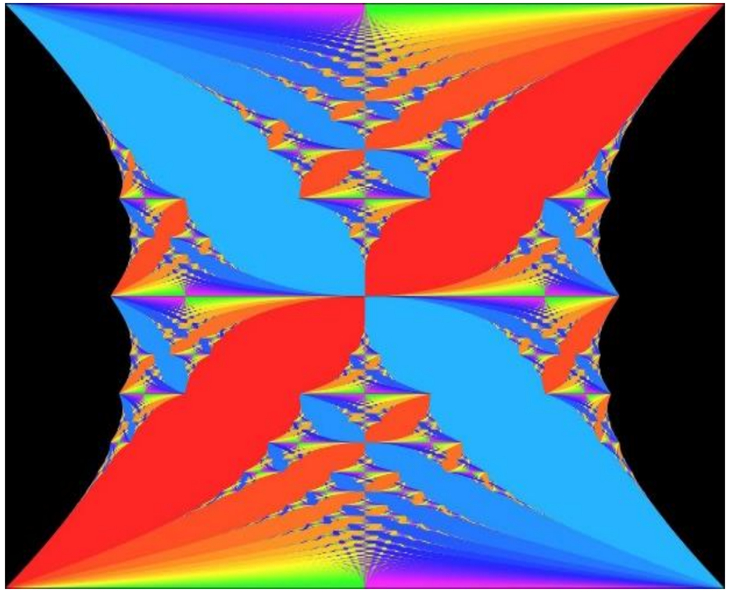
Quantum simulation

What is a quantum simulator? One possible definition is that of an experimental system that reproduces the physics of a precisely defined Hamiltonian*. However, the quantum simulator might provide an analogue that allows us to experimentally address intriguing questions that are not directly tractable in the laboratory. A second class of simulators deals with objectives that are not accessible via classical computation and may be employed to better understand and enable the design of exotic materials.

*Hamiltonian is an operator corresponding to the sum of the kinetic energies plus the potential energies for all the particles in the system

Quantum simulations by Google

Google especially focus on quantum algorithms for modelling systems of interacting electrons with applications in chemistry and materials science.



Hofstadter butterfly (1976)

It's called the Hofstadter butterfly (1976) and it's actually a map of how electrons behave in a strong magnetic field. Every split and shift of these subatomic particles are rendered by the photons inside of Google's quantum chip.

This was made possible by quantum simulators, which are special-purpose quantum computers. Even if quantum simulators can't solve any problem like theoretical quantum computers could, they can be used to solve specific problems.

Quantum-assisted optimization

Optimization deals with finding the best solution to a problem (according to some criteria) from a set of possible solutions

- Now **Google** is developing hybrid quantum-classical solvers for approximate optimization. Because discrete optimizations in aerospace, automotive, and other industries may benefit from hybrid quantum-classical optimization.

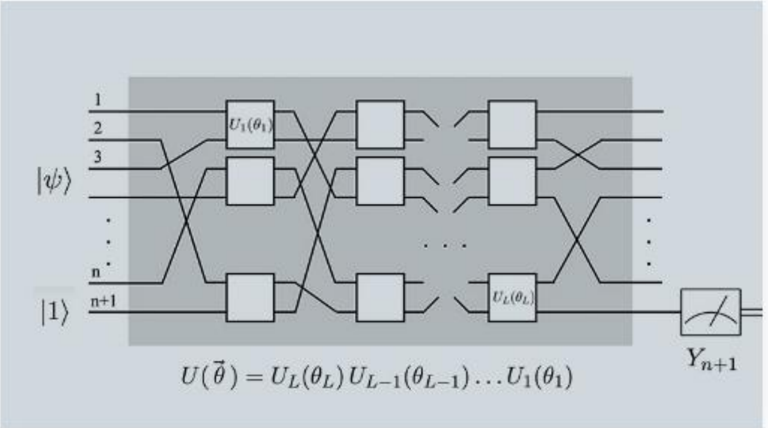
- Traditional quantum algorithms, such as Shor's factorization algorithm and Grover's search algorithm, can be statically compiled with a high level of optimization using known input parameters. With hybrid algorithms, some of a quantum program's input parameters can change each iteration. For example, a compiler may spend hours optimizing for quantum instructions that include quantum rotations for specific input angles to solve a chemistry problem, but now we find that the angles change every iteration. This suggests that we need a partial compilation strategy in which programs are optimized for unchanging parameters, but then quickly re-optimized each iteration for parameters that change.

Quantum neural networks

- Google constructs a model of quantum neural networks that is specifically designed to work on quantum processors that are expected to be available in the near term.
- Encoding a neural network within qubits gives an exponential advantage in storage capacity, while the algorithms and also an increase in processing speed. This means that we expect to run larger neural networks faster on a quantum processor than we could do using a standard computer. The Hopfield network itself has an application as a pattern recognition system, as well for solving the travelling salesman problem.

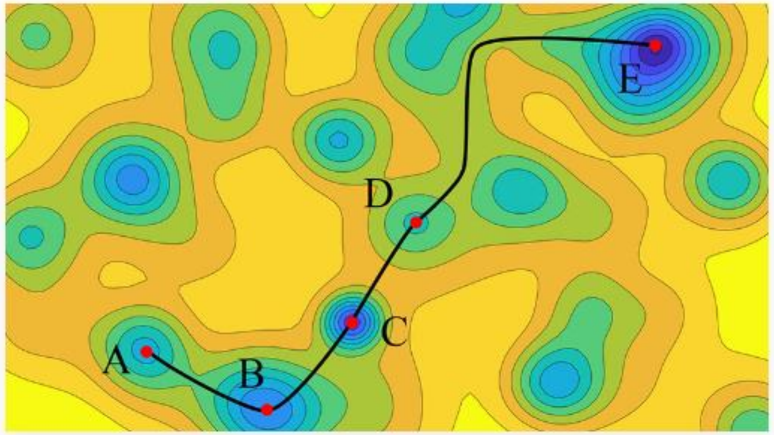
Since the technological implementation of a quantum computer is still in a premature stage, such quantum neural network models are mostly theoretical proposals that await their full implementation in physical experiments.

Near-term applications by GOOGLE



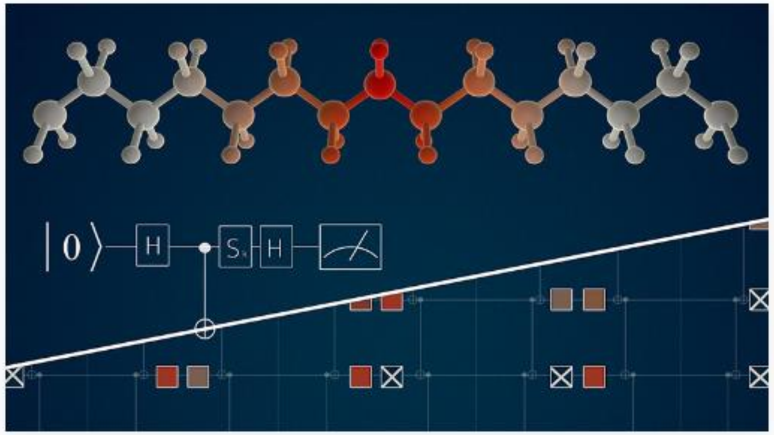
Quantum Machine Learning

We are developing hybrid quantum-classical machine learning techniques on near-term quantum devices. We are studying universal quantum circuit learning for classification and clustering of quantum and classical data. We are also interested in generative and discriminative quantum neural networks, that could be used as quantum repeaters and state purification units within quantum communication networks, or for verification of other quantum circuits.



Quantum Optimization

Discrete optimizations in aerospace, automotive, and other industries may benefit from hybrid quantum-classical optimization, for example simulated annealing, quantum assisted optimization algorithm (QAOA) and quantum enhanced population transfer may have utility with today's processors.



Quantum Simulation

The design of new materials and elucidation of complex physics through accurate simulations of chemistry and condensed matter models are among the most promising applications of quantum computing.

Speaker: Vladislav Podkovyrkin U1710275

Quantum A.I.

Quantum Computing merges two great scientific revolutions of the 20th century: computer science and quantum physics. Quantum physics is the theoretical basis of the transistor, the laser, and other technologies which enabled the computing revolution. But on the algorithmic level, today's computing machinery still operates on "classical" Boolean logic. Quantum computing is the design of hardware and software that replaces Boolean logic by quantum law at the algorithmic level. For certain computations such as optimization, sampling, search or quantum simulation this promises dramatic speedups. We are particularly interested in applying quantum computing to artificial intelligence and machine learning. This is because many tasks in these areas rely on solving hard optimization problems or performing efficient sampling.

Quantum Artificial intelligence

The theories of quantum computation have some interesting implications in the world of artificial intelligence. The debate about whether a computer will ever be able to be truly artificially intelligent has been going on for years and has been largely based on philosophical arguments. Those against the notion suggest that the human mind does things that aren't, even in principle, possible to perform on a Turing machine.

The theory of quantum computation allows us to look at the question of consciousness from a slightly different perspective. The first thing to note is that every physical object, from a rock to the universe as a whole, can be regarded as a quantum computer and that any detectable physical process can be considered a computation. Under these criteria, the brain can be regarded as a computer and consciousness as a computation. The next stage of the argument is based in the Church-Turing principle and states that since every computer is functionally equivalent and that any given computer can simulate any other, therefore, it must be possible to simulate conscious rational thought using a quantum computer.

Some believe that quantum computing could well be the key to cracking the problem of artificial intelligence but others disagree. Roger Penrose of Oxford University believes that consciousness may require an even more exotic (and as yet unknown) physics.

Tool by GOOGLE
for developing quantum algorithms

An open-source quantum framework for building and experimenting with noisy intermediate scale quantum (NISQ) algorithms on near-term quantum processors

Cirq

Cirq is a software library for writing, manipulating, and optimizing quantum circuits and then running them against quantum computers and simulators. Cirq attempts to expose the details of hardware, instead of abstracting them away, because, in the Noisy Intermediate-Scale Quantum (NISQ) regime, these details determine whether or not it is possible to execute a circuit at all.

What is Google Cirq?

Cirq is

- An open source Python framework for writing, optimizing, and running quantum programs on near term hardware.

```python
import cirq

# Define a qubit.
qubit = cirq.GridQubit(0, 0)

# Create a circuit (qubits start in the |0> state).
circuit = cirq.Circuit.from_ops(
    cirq.X(qubit)**0.5,  # Square root of NOT.
    cirq.MeasurementGate('result').on(qubit)  # Measurement.
)

print(circuit)
```

```
(0, 0): ───X^0.5───M───
```

Tool by GOOGLE
for simulating and translating problems in chemistry

An open-source platform for translating problems in chemistry and materials science into quantum circuits that can be executed on existing platforms

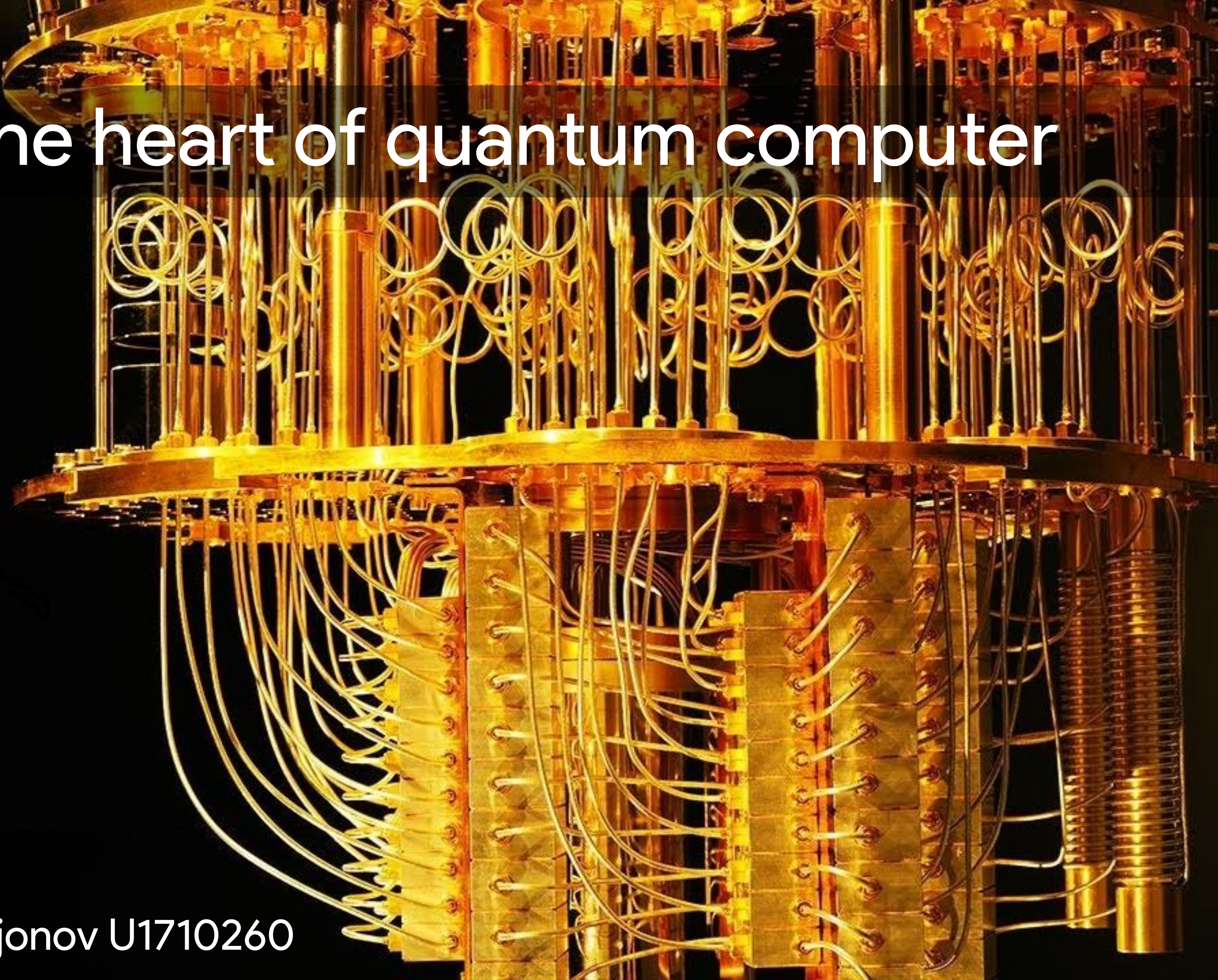
OpenFermion

One way to think of **OpenFermion** is as a tool for generating and compiling physics equations which describe chemical and material systems into representations which can be interpreted by a quantum computer1. The most effective quantum algorithms for these problems build upon and extend the power of classical quantum chemistry packages used and developed by research chemists across government, industry and academia.

All about the heart of quantum computer

Newest Google Quantum Processor –

size, materials, structure, qubits number, cryostat, temperature, vacuum, position, signals, read & control.

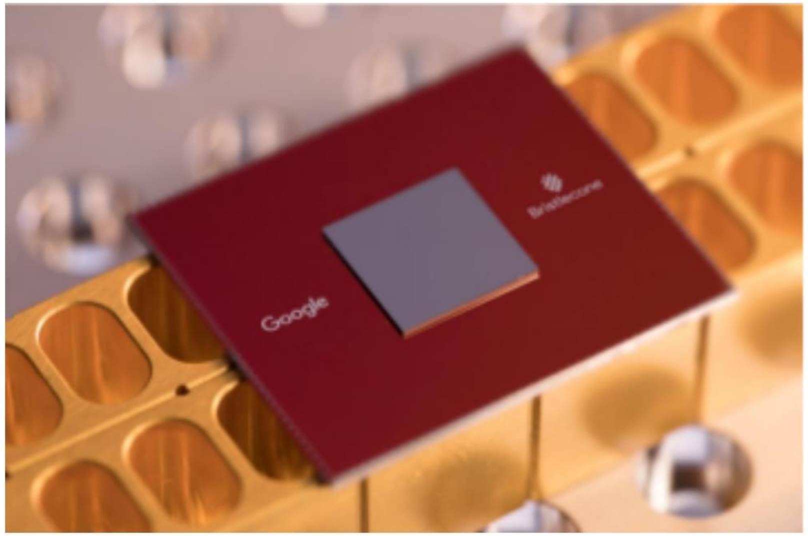


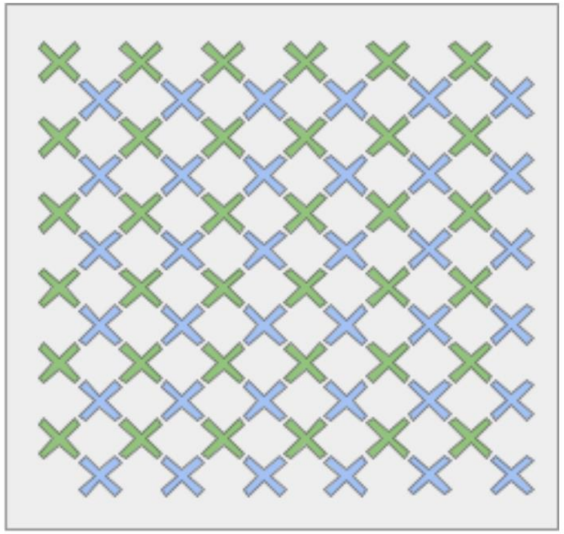
Speaker: Jamshid Khakimjonov U1710260

Bristlecone - Google's New Quantum Processor

What does a quantum computer look like?
Let's take a look at the actual hardware they are building at Google.

Qubits are resonant electrical circuits, made of patterned aluminium on a silicon chip that slosh electrical current back and forth at two different energy levels to encode the quantum 0 to 1 states. Example of one of quantum chips – Google's newest chip Bristlecone. Each chip features 72 qubits. It's about a size of a quarter. We want each qubit to behave as one single quantum object, with two levels. Any other particle interacting qubit from it's environment pulls away from this two-level idea.



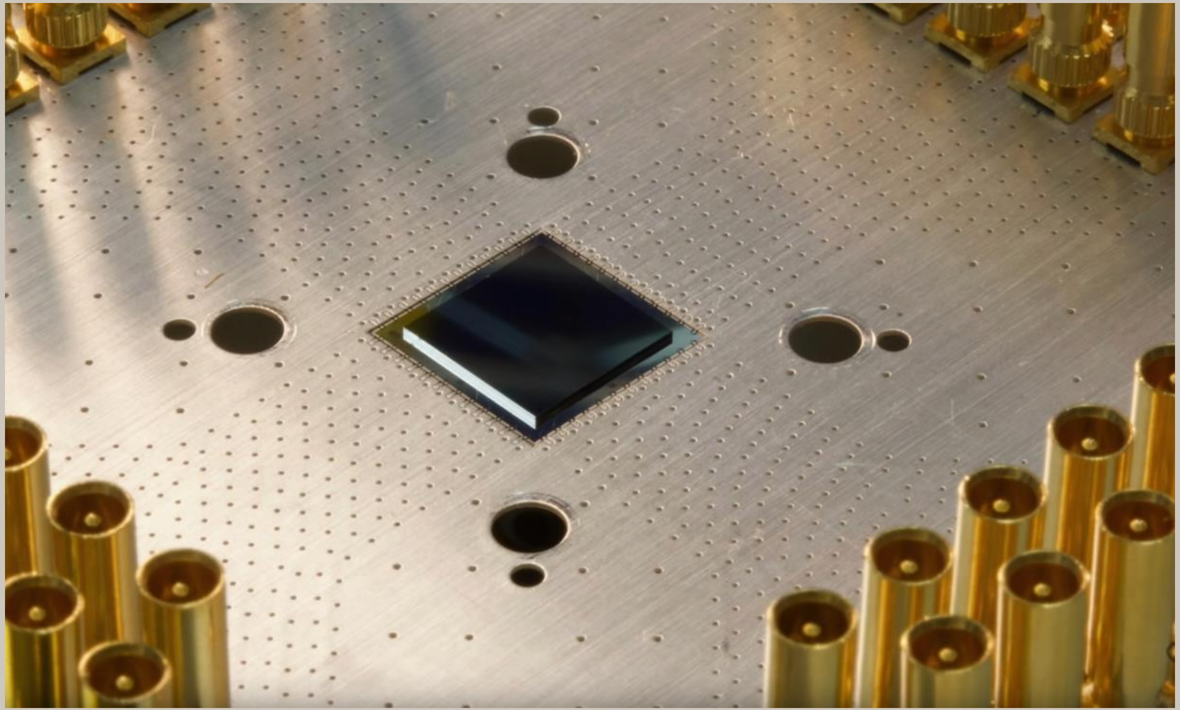


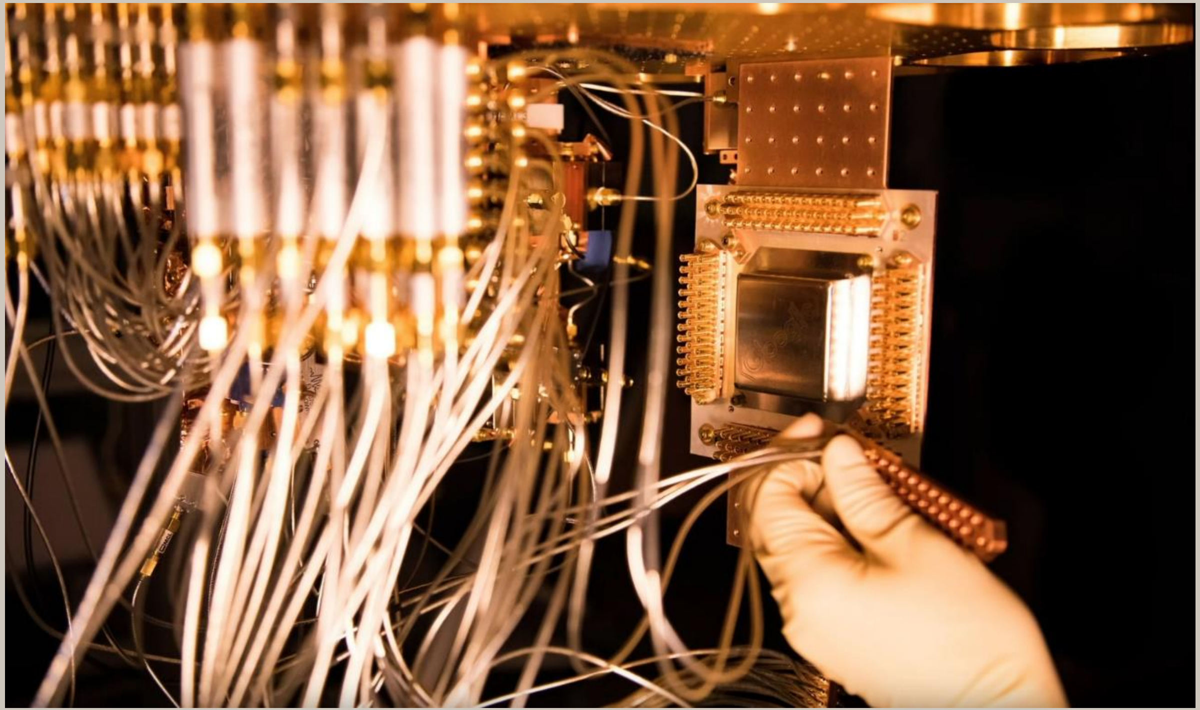
Bristlecone is Google's newest quantum processor (left). On the right is a cartoon of the device: each "X" represents a qubit, with nearest neighbor connectivity.

Control the qubits efficiently

A first step toward building clean qubits is to build the qubit circuits out of superconducting materials, which experiences ne electrical loss. Superconductors perform only at very low temperatures. And they operate qubits in a cryostat at less then 50 millikelvin, just a fraction of degree above absolute zero. The cold temperatures and vacuum inside a cryostat also contribute to keeping the qubit environment clean. The cryostat consist of a series of nested plates and cans. The warmest stage is at top, and it get’s colder, as you go down. All the equipment is the central core of the cryostat is responsible for getting things cold. Their hardware is installed around the edges and on the bottom coldest plate.

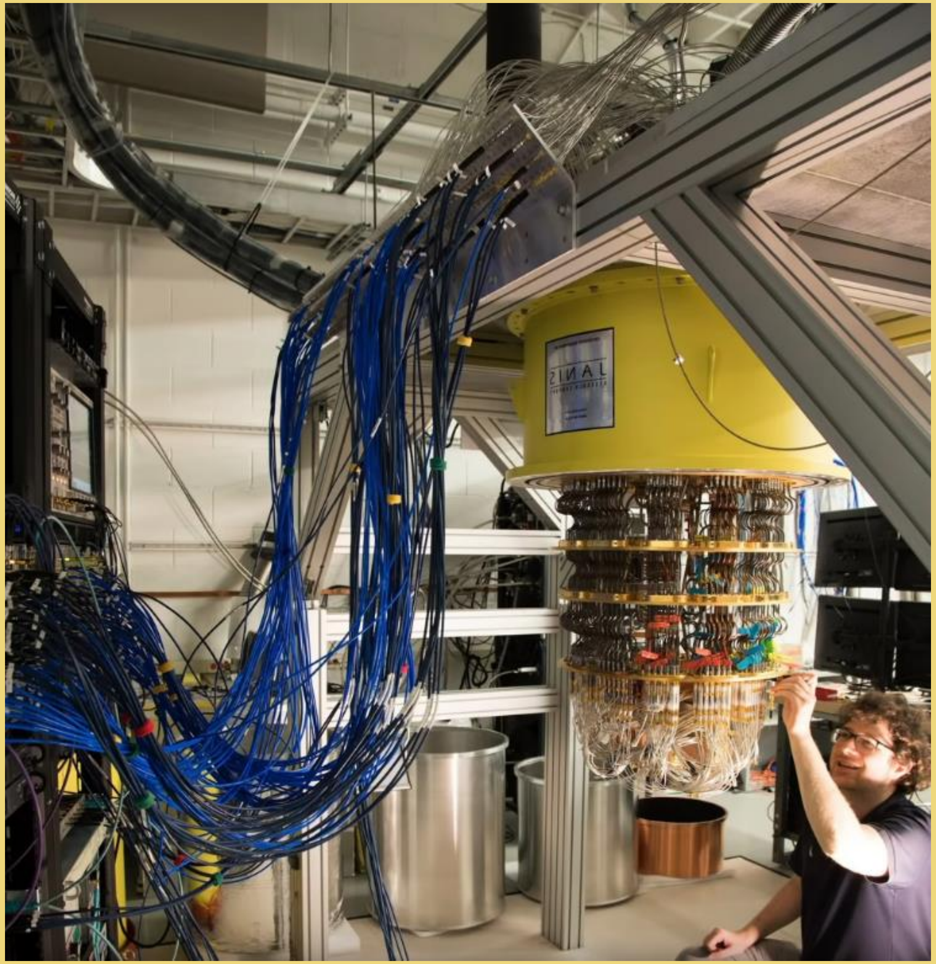
Qubit chips position





Each qubit chip must be mounted in a package, which holds the chip at millikelvin temperatures and bridges the gap between cables and a small chip.

Read & Control of qubits by pulses

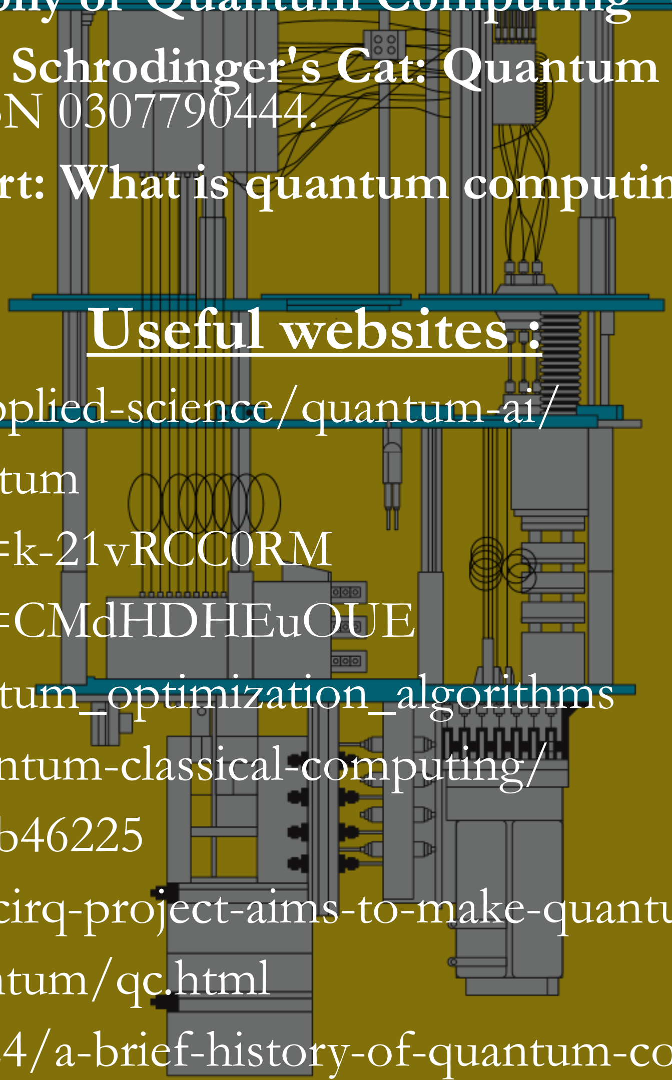


To address the packed chip, electronics outside the cryostat send signals. Each carry electrical signals from room temperature all the way down to the coldest stage, while leaking only the small amount of heat. A large heat load would prevent the cryostat from reaching its millikelvin base temperature. A collection of filters and amplifiers outfits each cable for its specific task. The electronics outside cryostat are controlled by code running on a computer. They generate precisely calibrated electrical signals, shaped pulses of microwave radiation, which are send to control and read the qubits.

Conclusion

We hope you enjoyed digging into some quantum computing basics with us in these last 30 minutes. We talked about the meaning of the word “quantum”, in particular, as it relates to computer hardware. Considering the idea of a single qubit in superposition, and adding more qubits we saw that each time we add another qubit, it takes twice as much information to describe the whole pile of them. That’s what really distinguishes a quantum computer from a regular one.

References



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- Gribbin, John (2011). **“In Search of Schrodinger's Cat: Quantum Physics And Reality”.** Random House Publishing Group. p. 234. ISBN 0307790444.
- Peter Schottenfels , **“Ask a Techspert: What is quantum computing?”**, Tech Newbie (2019)

Useful websites :

- https://ai.google/research/teams/applied-science/quantum-ai/
- https://en.wikipedia.org/wiki/Quantum
- https://www.youtube.com/watch?v=k-21vRCC0RM
- https://www.youtube.com/watch?v=CMdHDHEuOUE
- https://en.wikipedia.org/wiki/Quantum_optimization_algorithms
- https://www.sigarch.org/hybrid-quantum-classical-computing/
- https://ai.google/research/pubs/pub46225
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- http://www.physics.open.ac.uk/quantum/qc.html
- http://wavewatching.net/2012/03/24/a-brief-history-of-quantum-computing/
- https://github.com/quantumlib/Cirq